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MAINTAINABILITY, IN FLIGHT AND GROUND

NERVA Program, Contract SNP-1

May 1970

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MAINTAINABILITY, IN FLIGHT AND GROUND

NERVA Program

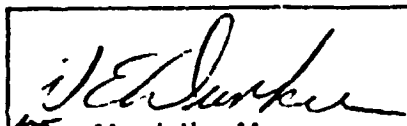



Contract SNP-1

May 1970

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- A Memo 7831:6246M J. C. Courtney to W. E. Stephens/A. D. Cornell
dated 25 March 1970 Subject: Estimate of Post-Shutdown NERVA
Radiation Environment

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I. INTRODUCTION

The purpose of this trade study is to provide maintainability input to the reference-engine definition. Although the maintainability program will continue for the duration of engine development, the effort under Trade Study 1003 was limited to support of engine definition during the second quarter of Contract Year 1970.

The space maintenance system, when selected and defined, will affect the cost of component maintenance, and will have a major effect as to which level of assembly (stage, engine, component, or part) replacement maintenance capability should be provided from an overall program cost standpoint. To partially compensate for the current lack of knowledge as to how the NERVA engine will be maintained in space, feasibility concepts of potential space maintenance methods were examined, and effects on engine design were evaluated and provided for when maintainability obviously benefited without severe detrimental effects on weight, reliability, or cost.

Future maintainability design changes resulting from additional knowledge gained as the program matures should be relatively minor.

II. OBJECTIVE

A. GENERAL

Provide maintainability input to reference-engine definition by February 16 1970.

B. DETAIL

1. Determine from a cost-effectiveness standpoint whether or not the engine should be replaceable on the nuclear ferry vehicle and whether or not the lower engine module (consisting of the pressure vessel, reactor, nozzle assembly, and skirt) should be replaceable on the engine.

2. Determine which components should be maintained and the degree to which components should be modularized.

3. Provide maintainability guidelines for engine and component configuration that will optimize maintainability with other engine parameters within the constraints of schedule and available data.

III. SUMMARIZED RESULTS AND CONCLUSIONS

A. The current engine design should provide for replacing all valves, actuators, and turbomachinery through maintenance actions.

B. To simplify replacement operations and reduce the number of joints and connections components are to be integrated into related modules.

C. The capability to replace the engine on the vehicle in space appears to be the most important maintenance capability to be provided because the resulting extension of the nuclear ferry life affords significant opportunities for reducing program costs. If the vehicle concept wherein propellant tanks delivered to orbit by the Earth Orbit Shuttle are then combined into a module of tanks that become part of the nuclear ferry is chosen, a type of engine installation on the ferry would be required after each mission. It may also prove more cost effective to change engines to accommodate the different shielding requirements of manned or unmanned missions than by modifying the shield configuration of an engine mounted on the vehicle.

The capability to replace the engine must be accounted for in designing the engine-vehicle interface and must be provided for in the space support equipment and facilities. Major cost expenditures would be justified to achieve fast, simple engine replacement. Detailed design of the engine-vehicle interface need not be shown on the current reference engine, but the requirements must be recognized and, early in the program, total coordination of this design with the space equipment and facilities be effected. The engine probably should be replaced on the vehicle remotely. Engineering evaluation is required to determine what capability should be provided by the vehicle and what should be provided by external space support equipment.

D. It is not cost effective to maintain the engine to provide an

extended life by replacing a module containing the reactor on the rest of the engine, as the program hardware cost reduction does not appear to exceed the cost of providing this maintenance capability. A special separation plane dividing the engine into an upper and lower engine module should not be provided in current engine design.

E. Maintainability guidelines for engine and component configuration design were developed by considering nuclear engine maintenance during ground testing, maintenance on the launch pad, and maintenance in space. These guidelines emphasize easy replacement of components and are listed as follows:

1. Arrange components, piping, electrical harnesses and structures to provide more than normal accessibility.
2. Avoid loose parts during replacement activities by designing so parts are captive to the item being removed.
3. Provide for simplicity of motions and attachments in designing replacement capability. For example, use single axis motion to separate and install items.
4. Keep separation and replacement loads as low as practical.
5. Where possible, avoid a requirement for special equipment or tools and minimize through standardization the number of different tools required to accomplish maintenance operations.
6. Minimize the disturbance of parts or components that are not being replaced.
7. Design for maintenance actions in space should consider the problem of excessive shock loads that could result from the initial

impact of floating masses as replacement items are brought to the next assembly for installation. Provisions must be made to avoid contact at an angle or contact at significant velocity.

8. When practical, incorporate methods of ensuring precise alignment into the design of mating parts. For replacing the engine in space a method such as cascaded guide pins will be required to effect gross, close, and precise alignment as the engine is brought to the vehicle for installation.

IV. TECHNICAL DISCUSSION

A. PRELIMINARY MAINTAINABILITY (M) REQUIREMENTS

The maintainability requirements that were used as the basis for this study are those defined in the NERVA Program Requirements Document (NPRD), Release No. 6 dated 21 November 1969, and those transmitted by Technical Directive 70-15. The maintainability requirements specified in the NPRD are quoted as follows:

(a) The engine shall be designed and constructed to meet the following requirements:

(1) All mission-critical components external to the reactor pressure vessel and nozzle will be maintainable by repair, replacement or substitution (switching or redundancy) before and after operations. Trade studies will be conducted to investigate: (a) the extent to which modular versus individual-component designs affect reliability, maintainability and performance (including weight); and, (b) the extent to which remote or direct maintainability will be employed.

(2) Such maintenance will be achievable during non-operating periods in the mission.

(3) All mission-critical components will be capable of functional and electrical checks remotely after engine assembly or engine maintenance.

(4) It will be possible to purge the engine by an external source of inert gas prior to ground operation or launch.

(5) The engine will be remotely installed and removed from engine test facilities.

(6) After space operations, (manual) maintenance will not be required in excessive radiation environments.

(7) For the storage periods, previously specified, no periodic routine engine maintenance will be required.

(b) Trade-off studies, concurred in by SNPO, will determine the advisability of designing and constructing the engine such that it is replaceable on the stage; or that the reactor/pressure-vessel/nozzle assembly is replaceable on the engine. The Trade-off studies shall also address themselves to the question of disposal of these assemblies.

(c) A maintenance program and program plan shall be provided in accordance with AFSCM 310-1 and AFLCM 310-1. This program and plan shall also be in accordance with the following sections of this NPRD:

(1) Page 18, Section (3) and Page 19, Section (4): diagnostic instrumentation for failure detection and display of information in-flight:

(2) Page 21, Section (1): trend-data program; and

(3) Page 22, Section (2): certification of deliverable hardware.

The plan shall consider, in addition, the logistical requirements of engine maintenance in earth orbit or elsewhere in space.

(d) Utilization of maintainability concepts may be necessary to achieve the required reliability over the endurance stated in Section III.B.1.b. However, maintainability will not be used as a substitute for reliable design. The maintainability program will be developed to

extend the results of the reliability design process described in Section III.3.8 to aid, where necessary, in achieving the reliability requirement.

Technical Directive 70-15 augments and supplements these NPRD requirements, and these two documents establish the maintainability requirements for this trade study.

B. MAINTENANCE CONSIDERATIONS

Concepts for maintaining the NERVA engine during ground testing, on the launch pad, and during the operational phase in space have been examined from a feasibility standpoint to identify design requirements that should be included as part of the reference engine. Maintenance experience applicable to ground-testing the NERVA engine was acquired during the technology test program, and test-site maintenance facilities, equipment, and technical capability were proven at the Nuclear Rocket Development Station in Nevada. Extensive maintenance experience applicable to NERVA launch-pad operations has been acquired on liquid and solid rocket engines prior to launch at Cape Kennedy and Vandenberg, AFB.

The NERVA engine on the launch pad will not have been operated at any appreciable power; consequently, without the accompanying radiation environment, all rocket launch experience becomes applicable. Little or no experience is available that is applicable to maintaining a nuclear rocket engine in the radioactive, hard-vacuum, weightless environment of space; and because space maintenance methods may require additional consideration that could affect early design of the engine, this study will mainly concentrate in this area.

1. Maintenance in Space

a. Introduction

Methods for maintaining a nuclear engine in space have not yet been established, and the concepts are in their infancy. Many studies of numerous alternatives must be completed before a space maintenance system is sufficiently defined to optimize an engine configuration for maintenance with that system. The main questions affecting engine design to be resolved as the engine and its potential space maintenance capability are defined are (1) what to maintain in space on the basis of a reasonable determination of the overall costs vs overall benefit (cost reduction) for providing a maintenance capability at a specific level of the assembly and (2) how to perform maintenance in space on the basis of a determination of the extent to which remote or direct maintenance will be employed. Partial answers to these questions have been determined by a simplified cost logic together with a feasibility examination of space maintenance concepts to define desirable engine design features.

b. What to Maintain

For determining what to maintain, the decision whether or not to provide replacement maintenance capability must be considered at each of the following levels of assembly:

Level of Assembly

Level 1	Nuclear vehicle
Level 2	NERVA engine
Level 3	Module of engine components
Level 4	Engine component
Level 5	Engine component part

To replace at one of the above listed levels of assembly constitutes a repair of all the higher levels. Also to replace at a given level does not eliminate the option of subsequent repair and return to service of that item.

The cost of in space maintenance capability will be high and cost considerations will determine the level of assembly at which replacement capability will be provided. Replacement is made at a specific level of assembly to extend the life of the higher-level assemblies and to reduce program hardware cost. Providing replacement capability at a level of assembly is justified when the total cost of the capability is less than the reduction in hardware costs.

Hardware costs with and without replacement maintenance capability are conveniently compared on the basis of hardware costs per mission. A reduction in hardware cost per mission due to replacement capability can be multiplied by the number of missions in the program to determine the maximum amount that should be spent to provide the replacement capability. The hardware costs per mission depend on the cost of hardware delivered to space and the expected average number of missions (N) that may be accomplished while operating at a required level of reliability. The term mission, as used here, represents an average of the nuclear shuttle missions in such terms as power cycles, burn times, duration, and months in space. For the purpose of this study, the 10-hr duration requirement for the engine expressed in the NERVA Program Requirements Document is expressed in number of missions as follows:

The 10-hr engine duration is equivalent to ten missions (1 hour = 1 mission). The operational engine in space will be utilized approximately one mission per month.

A formula for determining hardware costs per mission through the 4th level of assembly is shown in Figure 1. The 4th level

FIGURE 1

EFFECT OF MAINTAINABILITY ON HARDWARE COST PER MISSION

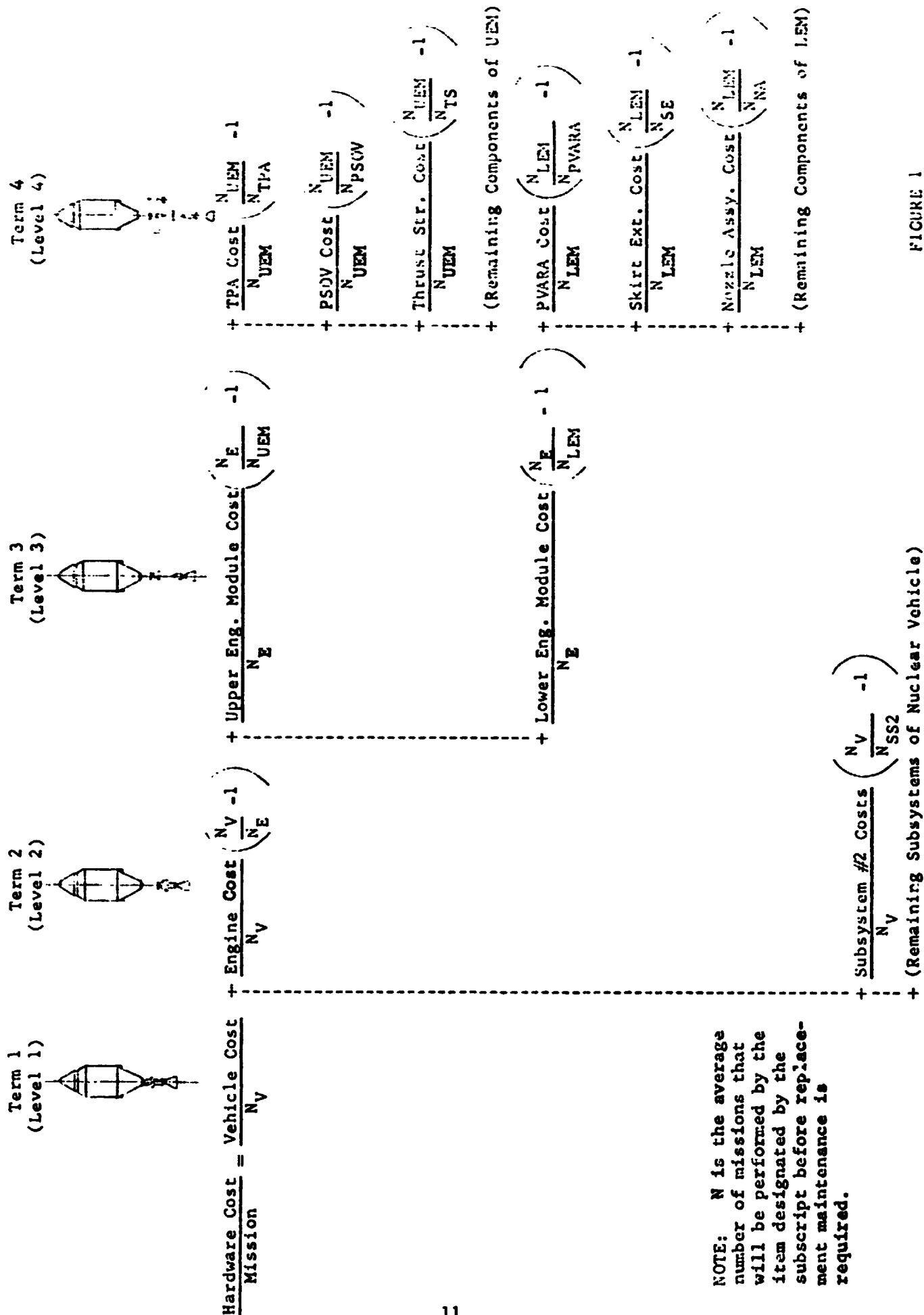


FIGURE 1

involves mission critical components and the formula may be expanded to cover the 5th or 6th level of assembly if desired. This formula is analyzed as follows:

(1) Analysis of the formula

(a) Number of Spare Items

The factor $\left(\frac{N_{\text{Higher Assembly}} - 1}{N_{\text{Item}}} \right)$ is common to

all terms but the top level of assembly. N_{Item} and $N_{\text{Higher Assembly}}$ are the expected mean number of missions of the item or the higher assembly respectively, that will be accomplished while operating at the required reliability before replacement maintenance is required. The factor represents the number of spare items required if the item is to be replaced through maintenance actions to increase the mean life of the higher assembly. As the higher assembly always includes the item, the number of spares is equal to the total number of items needed, $\frac{N_{\text{Higher Assembly}}}{N_{\text{Item}}}$, less one.

The total number of items required $\left(\frac{N_{\text{Higher Assembly}}}{N_{\text{Item}}} \right)$ must be a whole number.

If $\frac{N_{\text{Next Assembly}}}{N_{\text{Item}}}$ is equal to $\frac{N_{\text{Higher Assembly}}}{N_{\text{Item}}}$ the factor $\left(\frac{N_{\text{Next Assembly}} - 1}{N_{\text{Item}}} \right)$ becomes 0 and the term drops out of the equation. Also

if N_{Item} is greater than $N_{\text{Next Assembly}}$, the factor becomes a negative fraction indicating the value of the unused life in the original item when the life of the next assembly expires. This situation is similar to that for the life left in a fuel pump or radio when the life of an automobile has expired. Since any new higher-level assembly will contain new lower-level assembly items, it is assumed that there will not be recoverable value in the remaining operational life of component parts after the life

of the higher-level assembly expires. Therefore, when the factor is equal to 0 or a negative fraction, the cost of spare parts will be considered equal to 0 and the term will drop out of the equation.

NOTE

Without maintenance action, N for higher assemblies can never be greater than for any one of its component parts.*

In contrast, N for a higher assembly may be increased through the maintenance action of replacing mission-limiting items at any lower assembly level.

All terms drop out of the equation except the first term and the terms for items that will be replaced to extend the life of higher assemblies.

* Redundant component parts are considered as one item in this statement.

(b) Reliability, Mean Time Between Failure (MTBF),
and Mean Time Between Maintenance (MTBM)

Table 1 provides a preliminary listing of reliability and mean-time-between-failure data (Reference 9, Table 2). A mean-time-between-failures (MTBF), based on random distribution of failures, is shown both as predicted for the current state-of-the-art and as projected to the time when reliability goals are attained. MTBF based upon random distribution of failures (constant failure rate per unit time or per mission) cannot be used to schedule preventive maintenance because the probability for success per unit time or per mission does not diminish with time, and nothing is gained by replacing unfailed items. The items which exhibit random failure rates must be designed for the projected mean-time-between-failures shown in Table 1 where the probability of failure is acceptable or in single or multiple redundant groupings which provide an acceptable probability of failure. Corrective maintenance may be performed on failed redundant items prior to the next mission. However many components will have a lower true MTBF (not shown in the table) because of the effects of wear. These components will have to be identified and their true MTBFs will have to be determined. Trend data on these components as determined during the test phase will establish their true MTBF. On the basis of these data, the requirement for preventive maintenance of the item will be established by one of two methods. In the first method, diagnostic instrumentation will be selected and used during the operational phase to monitor wear and predict when maintenance must be accomplished. By this means replacement is effected only after the component has been used to maximum life conditions. In the second method, where it is not practical to monitor wear, statistical replacement may be scheduled at the small fraction of the wear out life which is consistent with the reliability requirements. In either case the value of N in the formula would be the mean number of missions between replacement maintenance. For example, the nuclear subsystem has been tested during the technology program. One unit was tested for a 1-hr duration, and other units were tested for shorter durations. For example purposes, assume that current

TABLE I

RELIABILITY AND MEAN TIME BETWEEN FAILURE

Item	Current Status			Projected Status			Remarks
	10 Hour Predicted Reliability*	MTBF Random (hr)	MTBF Wear (hr)	10 Hour Allocated Reliability*	MTBF Random (hr)	MTBF Wear (hr)	
NERVA Engine							
Nuclear Subsystem							
Fuel Elements	.832694	54.6		.995	2,000		
Cluster Hardware	.888498	85		.926823	3,140		
Cone Periphery	.900000	95		.927184	3,550		
Support Plate & Plena	.927623	4,200		.94329	149,000		
Internal Shield	.926585	2,920		.94037	103,800		
Reflector Assembly	.93360	15,620		.948195	554,000		
Control Drum Drive Assembly	.9450	200,000		.95859	7,100,000		
	.927194	3,560		.942088	126,400		
	.926446	2,810		.938998	99,800		
Support Structure Cooling Control System	.988672	878		.93677	31,000		
SSCV & Actuators (2 ea)	.928251	5,710		.93741	38,600		
SSEV (2 ea)	.928152	5,410		.93760	41,700		
CSOV (2 ea)	.928152	5,410		.93760	41,700		
CSCV	.926167	2,600		.93891	91,700		
Lines	.93460	18,510		.9485	667,000		
Propellant Feed System	.921809	1,220		.93766	42,700		
PSOV	.927862	4,670		.93710	34,500		
PDKV	.93300	14,300		.9480	500,000		
TBV	.927463	3,940		.93644	28,100		
TDCV	.928002	5,000		.93732	37,300		
BCV (2 ea)	.928002	5,000		.93732	37,300		
BBV (2 ea)	.927463	3,940		.93642	27,900		
TPA	.928771	8,130		.93831	59,200		
PIL	.9480	500,000		.9567	3,030,000		
PDL	.93780	45,450		.9478	455,000		
TIL	.93740	38,460		.9477	435,000		
TEL	.93740	38,460		.9477	435,000		
TBL	.93740	38,460		.95260	1,350,000		
Engine Purge Unit	.928988	9,880		.935	20,000		

* Subscript denotes number of 9s, i.e., .926 = .996
Data are from Reference (9) - see Table 2.

TABLE I (cont.)

Item	Current Status			Projected Status			Remarks
	10 Hour Predicted Reliability*	MTBF Random (hr)	MTBF Wear (hr)	10 Hour Allocated Reliability*	MTBF Random (hr)	MTBF Wear (hr)	
Propellant Feed System (cont.)							
Pneumatic Stage Tank Press.							
SPKV	.93280	13,900		.94794	435,000		
SPSL	.93300	14,300		.9480	500,000		
	.9480	500,000		.9440	167,000		
Destruct Subsystem	.9420	125,000		.9577	4,350,000		
Nozzle Assembly Subsystem	.941114	112,500		.93746	39,400		
Nozzle	.92280	1,390		.93794	48,500		
Nozzle Skirt Extension	.92830	5,880		.94515	206,000		
Instrumentation & Control Subsystem	.965438	284		.93014	10,100		
EPIC	.971228	340		.931834	12,200		
Wiring Harness	.93854	68,500		.95585	2,410,000		
Nonnuclear Instrumentation	.927088	3,430		.94173	121,000		
Nuclear Instrumentation	.927088	3,430		.94173	121,000		
Thrust Structure Subsystem	.93640	27,800		.950	1,000,000		
External Shield Subsystem	.9465	286,000		.960	10,000,000		
Gimbal Assembly Subsystem	.93425	17,400		.9484	625,000		
Gimbal Actuators & Support Rods	.93550	22,200		.94875	800,000		
Gimbal Block	.93875	80,000		.95652	2,870,000		
Pressure Vessel & Closure Subsystem	.94	100,000		.957	3,330,000		

*Data are from Reference (9) - see Table 2.

state-of-the-art predictions would place MTBF due to wear out of this subsystem in the neighborhood of 3 to 5 hours. The projected MTBF for the NSS during the operational phase might still be 3 to 5 hours or might be 10 or 20 or more hours if a major breakthrough is possible and if the cost of this breakthrough is cost effective and within the funding constraints. In subsequent paragraphs, where this formula is applied to establish the lowest level of assembly that should be provided with replacement capability, it was assumed that the Mean Time Between Maintenance (N) was 10 missions for this subsystem.

(c) Redundancy and Mean Time Between Maintenance

Redundancy is used to increase the reliability of a component or system. This occurs when the redundant component is brought on stream with the failure of the original component (passive or standby redundancy) or when both components are on stream at all times and it takes a failure in both components to abort the component operation (active redundancy). Redundancy is being applied to the majority of components on the NERVA engine that are not part of the basic structure or the pressure vessel and nozzle. This redundancy is highly effective by increasing the probability that the engine could complete either a single mission or a group of missions without mission failure. However, if it is defined that the failure of one component of a redundant pair of components represents a system failure that requires corrective maintenance prior to the start of the next mission, the probability for completing the 10-hour engine life without maintenance is actually less than for the case where a single non-redundant component is utilized. This causes a corresponding reduction in MTBM (N).

(2) Application of the Hardware Cost Formula

When the mean time between replacement, expressed as N in the cost formula, is established for each component and the total cost for various maintenance capabilities in space is estimated with some degree

of accuracy, it will be possible to estimate the cost effectiveness of maintenance at each level of assembly. However, with current knowledge and utilization of the logic contained in the preceding paragraphs, it is possible to make some assumptions and determine how much might be spent for maintenance capability - or for design breakthrough - and still be cost effective. The operational-hardware cost-per-mission formula (Figure 1) provides a method of determining the cost effectiveness in deciding whether or not to provide replacement maintenance capability for an item at a specific level of assembly. The reduction in hardware costs per mission can be determined by comparing the alternative of providing replacement capability with the alternative of not providing replacement capability. The reduction in cost per mission multiplied by the number of program missions determines the program hardware cost reduction resulting from that specific maintenance action. After a portion of this amount is used to provide the replacement capability, the remainder represents program savings; or, as program savings approach zero, the amount represents the maximum total cost for the maintenance capability that remains cost effective. The formula may be used to answer the following types of questions.

Question 1 What is the program operational-hardware cost without maintenance?

Answer Without maintenance, all terms except the first drop out.
 Program hardware cost = number of missions $\times \left(\frac{\text{Cost of vehicle in space}}{N_V} \right)$.

Question 2 What is the program operational-hardware cost if capability is provided for replacing the engine on the nuclear ferry in space and this capability extends the life of the vehicle from N_{V_1} , (unmaintained) to N_{V_2} (maintained)?

Answer Program hardware cost =

$$\text{number of missions} \times \left(\frac{\text{cost of vehicle}}{N_{V2}} + \frac{\text{cost of engine}}{N_{V2}} \left(\frac{N_V}{N_E} - 1 \right) \right).$$

Question 3 What maximum cost-effective amount could be spent as the total cost for providing this engine replacement capability?

Answer Answer to question 1 less answer to question 2; and, since N_{V1} (unmaintained) is equal to or less than N_E , the program hardware cost reduction = number of missions \times

$$\left(\frac{\text{cost of vehicle} - \text{cost of engine}}{N_{V2}} \left(\frac{N_{V2}}{N_E} - 1 \right) \right).$$

Question 4 What additional maximum cost-effective amount could be sent as the total cost for providing replacement capability for the engine's life-constraining component (mean time between replacement = N_C) if this extends the life of the engine from N_E (unmaintained) $\leq N_C$ to N_{E2} (maintained) $\geq N_{V2}$?

Answer Program hardware cost reduction =

$$\text{number of missions} \times \left(\frac{\text{Cost of engine} - \text{cost of component}}{N_{V2}} \left(\frac{N_{V2}}{N_C} - 1 \right) \right).$$

The cost formula (Figure 1) was used as expressed above for the cost evaluation of four alternative space maintenance concepts to determine what

should be maintained in space. These four concepts are shown and defined in Figure 2. Tables 2, 3, and 4 present the data and source of data used in applying the formula. The cost data are summarized in Table 5, and the four concepts are compared and discussed in the following paragraphs.

For the reference case, Concept 1, it is assumed that the nuclear ferry has a 10-mission life and is not maintained. The assumed 500-mission program utilizes 50 nuclear ferries. Hardware cost for the program is \$9,000,000,000.

For Concept 2, it is assumed that, for an unspecified additional cost for the capability, a 10-mission-life engine may be replaced on the nuclear ferry vehicle and, with vehicle maintenance, the nuclear ferry life may be extended to 20 missions. Thus, 25 nuclear ferries including engines with 25 spare engines can accomplish the 500-mission program. Compared with Concept 1, the program hardware cost reduction from Table 5 is \$4,157,000,000. This is the maximum additional cost for obtaining this capability that will result in a savings to the overall program. Table 6 presents similar breakeven costs for the additional capability when successive engine replacements are made to extend the nuclear ferry life beyond 20 missions. From the engine standpoint, this is an extension of Concept 2 with no additional effect on engine design, but it indicates an area for worthwhile investigation for programmatic savings.

For Concept 3, it is assumed that, for an unspecified additional cost for the capability, a 10-mission-life lower engine module consisting of the nuclear subsystem, nozzle and nozzle extension may be replaced on the engine and, with maintenance, the engine and vehicle life may be extended to 20 missions. Thus, 25 nuclear ferries including the engine and 25 spare lower engine modules consisting of the pressure vessel, reactor, nozzle assembly, and nozzle-skirt extension would be utilized to accomplish the 500 missions. Again from Table 5, the reduction in program hardware costs

COST CONSIDERATIONS
SPACE MAINTENANCE CONCEPTS

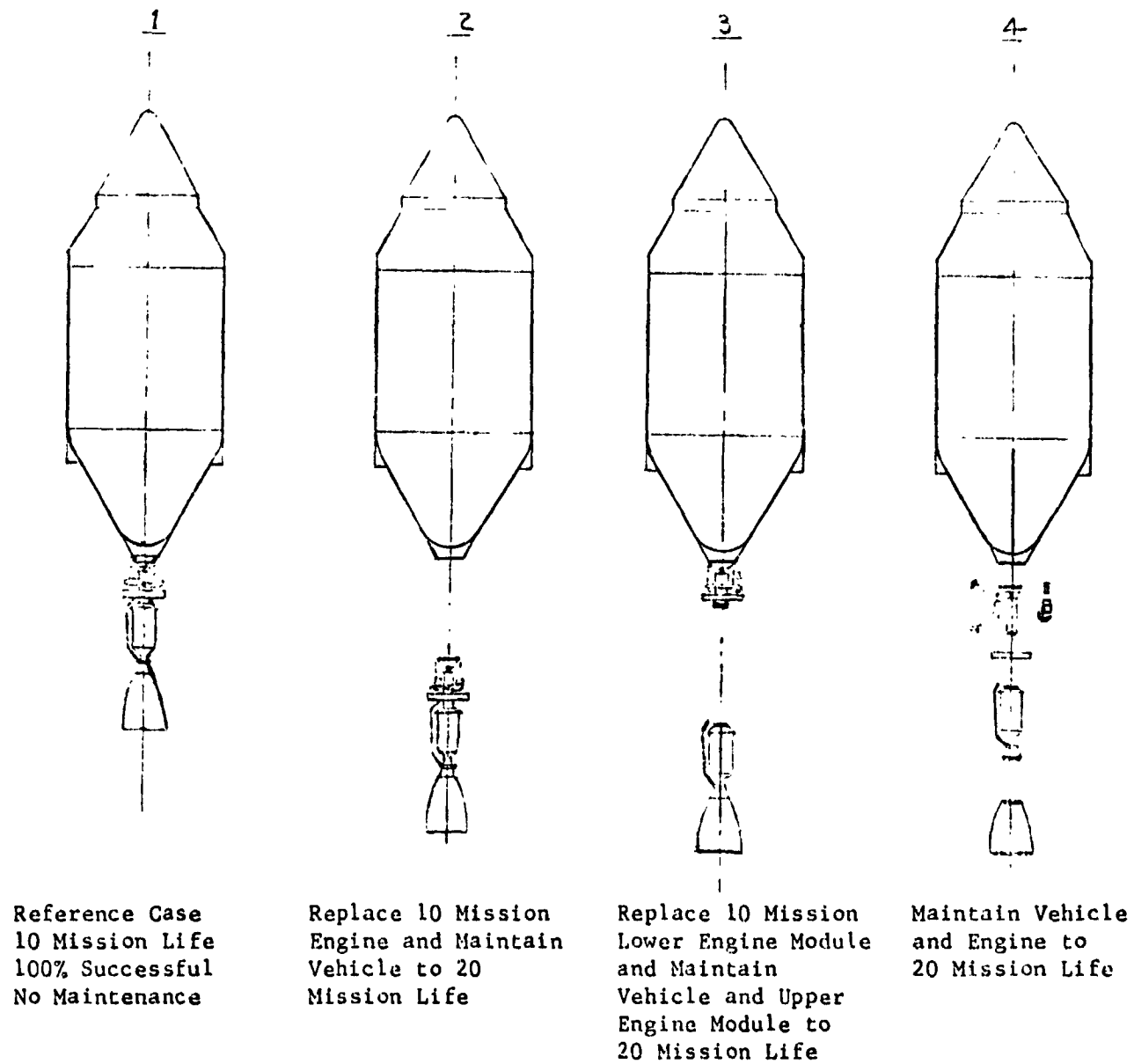


FIGURE 2

TABLE 2

REFERENCES USED AS SOURCE OF DATA

- Reference (1) NERVA Program Requirements Document
- Reference (2) Technical Directive 70-15
- Reference (3) Letter SDB:JJF, R. W. Schroeder to A. L. Feldman, Subject "Answers to AGC's Maintainability Questions", dated November 28, 1969
- Reference (4) Letter SI-1063, A. C. Sanderson to J. L. Dooling, Subject "WANL Input to AGC Trade Study 1003" dated December 11, 1969
- Reference (5) Hardware Unit Cost Developed for RN-DR-0188, Entitled "Cost Data on Long-Range Program Plan for Full-Flow Engine" dated December 1969 (Costs are based on current labor and material rates)
- Reference (6) S047-CP090290-Fi Mass Properties Analysis Report, Dated 2 February 1970
- Reference (7) Memo 7830:5159, T. E. Lavenda to Distribution, Subject "Preliminary Nuclear Vehicle Performance Estimate for Mission A, Reusable Interorbit Ferry (Hydrogen Capacity 300,000 lb), Dated 6 November 1969
- Reference (8) Review of NERVA Radiation and Shielding Studies, Briefing for Dr. Wernher VonBraun and Dr. Edward Teller, Dated 20 Sept 1969
- Reference (9) Memo E. J. West to R. W. Froelich, 7850:M0497, dated 16 March 1970, Subject: Reliability Apportionment of Current Reference-Engine Concept
- Reference (10) Memo 7410:0002, R. L. Rishel to J. J. Stewart, dtd 18 December 1969, Subject: Payload Sensitivity Factors for NERVA Reference Missions
- Reference (11) Memo 7831:6246M, J. C. Courtney to W. E. Stephens/A. D. Cornell, dtd 25 March 1970, Subject: Estimate of Post-Shutdown NERVA Radiation Environment
Attached
Appendix A

TABLE 3

ENGINE COST & WEIGHT DATA

<u>ITEM</u>	<u>COST</u>	<u>WEIGHT, lb</u>
Cost of Lower Engine Module		
Reactor & Control-Drum Actuators	\$7,293,000 ⁽¹⁾	13,610 ⁽³⁾
Nozzle and Skirt	603,000 ⁽²⁾	1,445 ⁽³⁾
Nozzle-Skirt Extension	112,000 ⁽²⁾	600 ⁽³⁾
Pressure Vessel and Closure	74,000 ⁽²⁾	1,743 ⁽³⁾
	<u>\$8,082,000</u>	<u>17,398⁽³⁾</u>
Cost of Upper Engine Module		
Support-Structure Coolant	\$ 248,400 ⁽²⁾	
Propellant Feed System	1,298,000 ⁽²⁾	
Stage Pressurization Valves	21,600 ⁽²⁾	
Thrust Structure	205,700 ⁽²⁾	
Gimbal	248,600 ⁽²⁾	
	<u>\$2,022,000</u>	<u>8,356⁽³⁾</u>
External Disk Shield	\$ 57,100 ⁽²⁾	10,000 ⁽³⁾
NERVA Engine	\$10,160,000 ⁽²⁾	35,754 ⁽³⁾

(1) Reference No. 4 (The cost of the reactor used here does not include reactor assembly and inspection costs.)

(2) Reference No. 5

(3) Reference No. 6

SOURCE OF DATA USED TO
COMPARE SPACE MAINTENANCE CONCEPTS 1, 2, 3, & 4

<u>ITEM</u>	<u>VALUE</u>	<u>SOURCE</u>
Nuclear Vehicle Usage Information		
Operational Phase	1980 through 1995	Ref. 3
Number in space at given time	1980-1984 3 Max, 1 min	Ref. 3
	1985-1989 6 max, 3 min	Ref. 3
	1990-1995 10 max, 5 min	Ref. 3
Number of engines consumed	1980-1995 66 max, 33 min	Ref. 3
Number of missions	1980-1995 500	Assumed
(Based upon assumed 50 engines consumed @ 10 missions per engine)		
Individual engine operational usage	1 hour/month	Ref. 3
Nuclear Vehicle Data		
Cost of delivery to earth orbit	\$150,000,000	Ref. 3
Cost on earth (including engine)	\$ 30,000,000	Assumed
Cost in earth orbit	\$180,000,000	Derived
Reliability for 10 missions	.990 at 90% prob.	Assumed
Payload outward bound	141,500 lb	Ref. 7
Hydrogen Capacity (total loaded)	300,000 lb.	Ref. 7
Payload outward bound cost of delivery	\$500/lb	Ref. 3
Earth-to-Earth-Orbit Shuttle Data		
Payload weight	50,000 lb	Ref. 3
Payload envelope	15 ft dia x 60 ft long	Ref. 3
Payload cost of delivery	\$100/lb ⁽¹⁾	Ref. 3
NERVA Engine Data		
Reliability	.995 at 90% Prob.	Ref. 1
Cost on Earth	\$10,160,000	Table 2
Weight (including external disk shield)	35,754 lb	Table 2
Delivery cost to earth orbit	\$3,570,000	Derived
Cost in earth orbit	\$13,735,000	Derived
Lower Engine Module (consisting of pressure vessel, reactor, nozzle assembly and nozzle skirt extensor)		
Cost on earth	\$8,062,000	Table 2
Weight	17,398 lb	Table 2
Delivery cost to earth orbit	\$1,740,000	Derived
Cost in earth orbit	\$9,822,000	Derived

- (1) Reference 3 provides an estimate that earth-to-earth-orbit shuttle payload costs will be \$100/lb in 1980 reducing to \$50/lb in 1995. \$100/lb was assumed for this comparison.

ALTERNATIVE NUCLEAR-VEHICLE DATA (BASED ON EOS DELIVERY TO ORBIT)

Dry weight	88,500 lb	Ref. 7
Cost on earth, including engine	\$30,000,000	Assumed
Cost in earth orbit	\$38,350,000	Derived

TABLE 5

COST OF OPERATIONAL HARDWARE

NUCLEAR FERRY	COST PER MISSION	COST OF 500- MISSION PROGRAM	RESULTING COST INCREMENT EFFECT ON OUTGOING PAYLOAD	COST OF CAPABILITY PLUS PROGRAM SAVINGS CONTAINED TO CONCEPT 1
<u>Concept 1</u>				
Assumptions:				
10-mission life	\$18,000,000	\$9,000,000,000	\$127/lb	Reference Case
No maintenance				
<u>Concept 2</u>				
Assumptions:				
Engine life - 10 missions				
Vehicle life - 20 missions	\$ 9,686,750	\$4,843,000,000	\$ 68.4/lb	\$4,157,000,000
Engine maintenance limited to replacement				
Vehicle maintenance as required				
<u>Concept 3</u>				
Assumptions:				
Lower engine life - 10 missions				
Upper engine life - 20 missions				
Vehicle life - 20 missions	\$ 9,491,100	\$4,745,000,000	\$ 67.1/lb	\$4,255,000,000
Maintenance of NSS limited to replacement				
Maintenance of upper engine and vehicle as required				
<u>Concept 4</u>				
Assumptions:				
Engine & vehicle life - 20 missions	\$ 9,000,000	\$4,500,000,000	\$ 63.6/lb	\$4,500,000,000
Maintenance of engine & vehicle as required				

TABLE 6

EXTENSION OF CONCEPT #2 TO SHOW POTENTIAL
BENEFIT OF EXTENDING VEHICLE LIFE BEYOND 20 MISSIONS
(BASED ON REPLACEMENT OF 10 MISSION ENGINES)

CONCEPT	NUMBER OF NUCLEAR FERRY MISSIONS	COST OF OPERATIONAL HARDWARE			CAPABILITY COST PLUS PROGRAM SAVINGS LAST 10 MISSIONS
		COST PER MISSION	COST OF 500 MISSION PROGRAM	RESULTING COST INCREMENT EFFECT ON OUTGOING PAYLOAD	
#1	10	\$18,000,000	$9,000 \times 10^6$	\$127/lb	----
#2	20	9,686,700	$4,843 \times 10^6$	\$ 68.4/lb	$54,158 \times 10^6$
	30	6,915,700	$3,457 \times 10^6$	\$ 48.8/lb	$1,385 \times 10^6$
	40	5,530,100	$2,765 \times 10^6$	\$ 39.1/lb	692×10^6
	50	4,698,800	$2,349 \times 10^6$	\$ 33.2/lb	416×10^6
	60	4,144,600	$2,072 \times 10^6$	\$ 29.3/lb	277×10^6
	70	3,748,700	$1,874 \times 10^6$	\$ 26.5/lb	194×10^6
	80	3,451,800	$1,726 \times 10^6$	\$ 24.4/lb	144×10^6
	90	3,220,900	$1,610 \times 10^6$	\$ 22.7/lb	104×10^6
	100	3,036,150	$1,518 \times 10^6$	\$ 21.4/lb	72×10^6

TABLE 6

compared with Concept 1 is \$4,255,000,000.

Comparing Concept 1 with Concept 2 shows that, in both concepts, it takes 25 nuclear ferries to complete the 500-mission program and, in Concept 1, it takes 25 additional spare engines whereas, in Concept 2, it takes 25 additional lower engine modules consisting of the pressure vessel, reactor, nozzle, nozzle skirt, and skirt extension. The program hardware cost reduction of \$73,000,000 (\$4,843,000,000-\$4,770,000,000, Table 3) between Concepts 2 and 1 would indicate that up to this amount could be spent to provide 20-mission capability to the upper engine module and to offset the cost of capability of replacing the lower engine module. Although \$73,000,000 is a sizable sum, it is not obvious that Concept 1 is really better than Concept 2. The \$98,000,000 is the result of \$196,000 per mission and is directly proportional to the number of missions estimated for the total program. For example, if the total program were estimated at 100 missions instead of 500 missions, the number \$98,000,000 would become \$19,600,000. Also, because a separation plane is actually required at the engine-vehicle interface to provide capability for the original engine installation, the separation plane between the lower engine and upper engine is a second separation and requires additional joints and connections in the electrical control and instrumentation wiring, in the piping, and in structural elements of the engine. The cost of capability, which affects the economic trade-off of whether or not to provide this second separation plane, include the following items:

- (1) Any degradation of engine reliability resulting from the additional separation plane.
- (2) Any weight increase and corresponding payload loss resulting from the additional separation plane.
- (3) Any degradation of performance and corresponding payload decrease as a result of the additional separation plane.

(4) The cost of providing 20-mission capability to the components of the upper engine module, including:

(a) Development through qualification

(b) Cost of space maintenance replacement capability

(5) Cost of the additional separation plane on the engine.

(a) Design and fabrication

(b) Development through qualification

(6) Cost of space capability for replacing lower engine module.

Information is not presently available for estimating the above costs with any reasonable accuracy. See Table 7 for the preliminary list of trade-off factors. These costs, when subtracted from the \$98,000,000, could leave a remainder that would represent programmatic savings. Any such savings would accrue to the program during the acquisition phase in the late 1970's and 1980's, but some of the costs for obtaining capability to replace the lower engine modules would occur during the development phase in the early 1970's. Therefore, it is doubtful that a separation plane dividing the engine into a lower engine module and an upper engine module will be desirable. It is inadvisable to expend a large sum of money to accomplish this capability in the current time period.

For Concept 4, it is assumed that, for an unspecified additional cost of capability, all engine components are maintainable by repair or replacement and that such maintenance of the engine would result in an extended life of the engine from 10 to 20 missions to match the maintained 20-mission life of the vehicle as assumed in Concepts 2 and 3. Thus, 25

TABLE 7

PRELIMINARY TRADE-OFF FACTORS
(BASED ON COST PER MISSION)

1. Cost of delivering payload via nuclear-vehicle shuttle (based on reference case of 141,500-lb outgoing payload and 300,000-lb LH₂ per mission).

<u>Cost Item</u>	<u>Cost Per Mission (\$/Mission)</u>	<u>Payload Cost Increment (\$/lb Payload)</u>
Hardware cost of 10-mission nuclear ferry in space at \$180x10 ⁶ --Concept 1	18,000,000	127
Propellant cost of LH ₂ at 300,000 lb/mission at \$100/lb	30,000,000	212
Cost of operating crew	?	?
Cost of support (ground and space)	?	?
Amortized cost of engine development until launch/500 mission	3,000,000	21
Amortized cost of vehicle development until launch/500 mission	<u>?</u>	<u>?</u>
Total payload delivery cost/mission (Government estimate - Reference 3)		\$500/lb

2. One pound of engine dry weight increase = 2.72 lb of payload decrease per mission (Reference 10)

Cost = \$1,360/mission.

3. One point of steady-state specific impulse (I_{sp}) decrease = 734 lb of payload decrease per mission (Reference 10)

Cost = \$367,000/mission.

4. Decrease in reliability due to design for maintainability vs increase in reliability resulting from the capability for maintenance during the 10-hr-duration requirement. This to be evaluated on individual-case basis.

nuclear ferries including 25 engines would accomplish the 500-mission program. From Table 5, the reduction in program hardware costs compared with those for Concept 1 could be as great as \$4,500,000,000. This represents the program savings that would occur if the unmaintained nuclear ferry with a 10-mission life of Concept 1 were changed, without any additional cost for capability, into an unmaintained nuclear ferry with a 20-mission life. Because the cost of maintenance capability is not included, this represents an unattainable maximum cost reduction that might result from repairing the replaced engine by providing replacement capability for the engine components. Concept 4 becomes identical with Concept 3 when the assumption is made that it is a 10-mission-life reactor that must be replaced to extend engine life to 20 missions. Also, Concept 4 approaches Concept 2 if additional engine components require replacement to attain the 20-mission engine life. If for example the maintenance associated with Concept 4 should entail replacement of the TPA and the lower engine module, the difference between Concept 4 and Concept 2 would only be \$52,000,000. This value is \$46,000,000 less than the \$98,000,000 difference between Concept 3 and Concept 2 discussed previously. This cost difference was generated on the basis of the estimated cost of the spare TPAs delivered in space by earth-orbit shuttle.

An additional cost-analysis facet to be considered is the possible savings that could result from the capability of being able to replace a component that has experienced an infrequent random failure. Such failures will occur when reliability is less than 100%, but the probability is quite small that a specific component of the NERVA engine will fail within its normal life cycle at any time during the 500-mission operational phase of the flight program. If the lower engine module as discussed in Concept 3 is used as an example, the cost of a spare unit delivered to space would be \$9,822,000. The difference between this figure and the \$13,735,000 cost of a complete engine delivered to space is \$3,913,000. This amount represents the hardware savings that would result only if the unfailed hardware still retained operational life equal to that of new hardware. In a similar example, if the TPA were the

component that experienced random failure, the difference between its cost of \$1,6000,000 delivered to earth orbit and the complete engine cost of \$13,735,000 is \$12,135,000. Because the cost of such maintenance capability in space would be hundreds of millions of dollars, the above values show that, even if three or four such failures were to occur during the entire flight program, it would not be cost-effective to provide engine maintenance capability beyond that of replacing the complete engine on the stage.

However, as discussed later in this report, the ability to replace components in the upper module would be worth the cost of maintenance on the launch pad and during the ground test program. On the launch pad, component replacement capability might permit local maintenance instead of requiring disassembly of a complex array of stages. Before reliability goals are achieved during the ground test program at the Nuclear Rocket Development Station in Nevada, the ability to replace a component represents significant savings as compared with discarding a complete engine when random failure occurs, especially when existing maintenance facilities such as the E-MAD building are available.

The incremental effect of hardware costs on payload provides an interesting perspective on the value of providing replacement capability at the different levels of assembly. On the basis of an outward-bound payload capability for the nuclear ferry of 141,500 lb, the cost increment due to operational hardware cost in Concept 1 is \$127.00/lb. This is reduced in Concept 2 to \$68.40/lb, in Concept 3 to \$67.10/lb, and in Concept 4 to \$63.60/lb. Excluding the cost of component spares and replacement capability, the maximum reduction in payload cost that is available from repairing an engine is \$4.80/lb, which is the difference between Concepts 2 and 4. The total cost of delivering outward-bound payload is approximately \$500.00/lb. It is apparent in comparing these two numbers that only a fractional percentage of program cost reduction is potentially possible by maintaining the engine beyond replacement of the engine on the vehicle.

The cost figures discussed in this section are based on a vehicle delivered to earth orbit by the Saturn V system at an estimated cost

of \$150,000,000 (see Table 4). The total in-space cost of \$180,000,000 was obtained by adding \$30,000,000 as the assumed vehicle cost on ground. If the eventual design of the nuclear vehicle permits earth orbital shuttle (EOS) delivery of the nuclear vehicle to earth orbit, the comparable cost of the vehicle in space would be approximately \$39,000,000. Although this reduction would change the cost numbers presented in this section, it would not affect the conclusions.

For example:

Assuming a 500 mission program and EOS delivery of the nuclear ferry to earth orbit, the unmaintained 10-mission ferry of Concept 1 would have a program operational hardware cost of \$1,950,000,000.

Replacing the 10-mission engine on the ferry and providing other vehicle maintenance as required to extend the ferry life to 20 missions (as in Concept 2) results in a program hardware cost of \$1,320,000,000. The reduction in hardware cost of \$630,000,000 appears to be sufficient to justify the provision of capability for engine replacement.

The cost of delivering the nuclear ferry to earth orbit does not affect any decision of whether or not to provide additional maintenance capability to the replaced engine.

c. How Space Maintenance Could be Performed and Effect on Current Engine Design

(1) General

Maintenance of the nuclear ferry vehicle and, more specifically, the NERVA engine in space provides many new problems compared

with maintenance on the ground. These problems stem from the space environment of hard vacuum and weightlessness and the radiation environment associated with a nuclear engine that has been operated. Man has always been a major contributor in the performance of maintenance actions on the ground, and his contribution will be required in space. The solutions to problems involved with protecting man from the above environments will determine to a large extent the degree of direct or remote maintenance that will be utilized in performing maintenance tasks. The total cost of this maintenance, as discussed in the last section of the report, will influence the planning decision to either maintain or discard items.

The following types of maintenance capability are candidates for accomplishing space maintenance actions on the nuclear ferry vehicle and the NERVA engine.

- (1) Provide direct manual capability - space environment.
- (2) Provide direct manual capability - shirtsleeve environment.
- (3) Provide human-operated remote capability.
- (4) Provide computer-operated remote capability.
- (5) Return defective item to earth for maintenance.
- (6) Provide any or all of above types of maintenance capability combined into a space maintenance system.

Undoubtedly, the last type of capability will be the one chosen for space maintenance where the types of capabilities for specific tasks will be selected on the basis of least total cost. This space

maintenance system will involve more than the engine and nuclear ferry and must consider space maintenance requirements of the propellant handling and servicing facilities, the earth-orbit shuttle, and the earth orbital station. The design of the space maintenance system that will eventually be made available in space may have a strong influence on engine design.

The types of maintenance actions to be accomplished in space are listed as follows:

(1) Routine operational maintenance on stage and engine.

(a) Replenishing of propellants and refurbishing of stage.

(b) Preoperational checkout.

(c) Postoperational checkout.

(2) Scheduled or Preventive Maintenance

Repair or replacement of time- or cycle depleted items.

(3) Unscheduled or Corrective Maintenance

Repair or replacement of items that have failed or have indicated potential failure.

The following concepts, concerning how these types of maintenance actions might be accomplished, have been examined so major influences on engine design can be recognized and incorporated in the definition of the current reference engine.

(2) Engine Space Maintenance System - Conceptual

In this section of the study, it is assumed that capability for engine replacement on the stage has been provided in the design of the engine-stage interface so as to permit rapid replacement (three days or less to mission readiness). By this maintenance action, the mean time to repair the nuclear ferry by replacing any malfunctioning part of the engine in space will be the time required to replace the engine. This mean time to repair may be reduced if it proves to be cost effective to provide additional capability in space or if maintenance by a man in a space suit proves feasible. By assuming an operational event in space that requires maintenance action and examining some of the alternative methods of accomplishing this action, it is possible to establish a preliminary definition of the capabilities required and determine how engine design might be affected if a specific alternative were eventually selected. This technique is used in the following portion of this report, and the following methods for accomplishing space maintenance tasks will be discussed.

- (a) Propellant servicing concept.
- (b) Pre- and postoperational checkout
- (c) Utilization of man in a space suit.
- (d) Maintenance actions involving engine replacement.
- (e) Disposition of an engine removed from space service.

(a) Propellant Servicing Concept

A possible propellant servicing concept is defined by assuming that the earth-to-earth-orbit shuttle (EOS) delivers propellant to the space propellant station in approximately 15-ft-dia by 60-ft-long tanks (Reference 3). A number of these tanks (twelve are shown in Figure 3) are used in combination as the servicing dewar for filling the nuclear-ferry tank in space. Empty tanks in the dewar system are expected to be replaced by full tanks without interrupting servicing operations. The whole system might be rotated at very low velocity (approximately 5-ft/sec peripheral velocity) so centrifugal force will supply pumping action for delivering propellant. It is assumed that, after a mission, the nuclear ferry will dock at this propellant station after cooldown flow to the engine has been terminated.

Five to ten nuclear ferries (Reference 3) may be in space operation at a given time. In Figure 3, two of them are shown docked in the propellant servicing area, with a flux map for 24 hr after shutdown (Reference 8) superimposed to indicate the resulting radiation field. This flux map points up the problem of having personnel enter the vicinity of more than one nuclear ferry or of working near the propellant servicing area.

The purpose in showing this concept is to illustrate a potential requirement for shielding the engine every time it returns from a mission to be docked in space in the same general area with other engines. Also, if the nuclear ferry is modified so that modules of these smaller tanks delivered by the EOS can be used for the nuclear ferry tank rather than a large tank requiring Saturn V delivery, replenishment activities between missions will require radiation protection. Potential use of such a shield to effect manual maintenance on the upper engine will be discussed later.

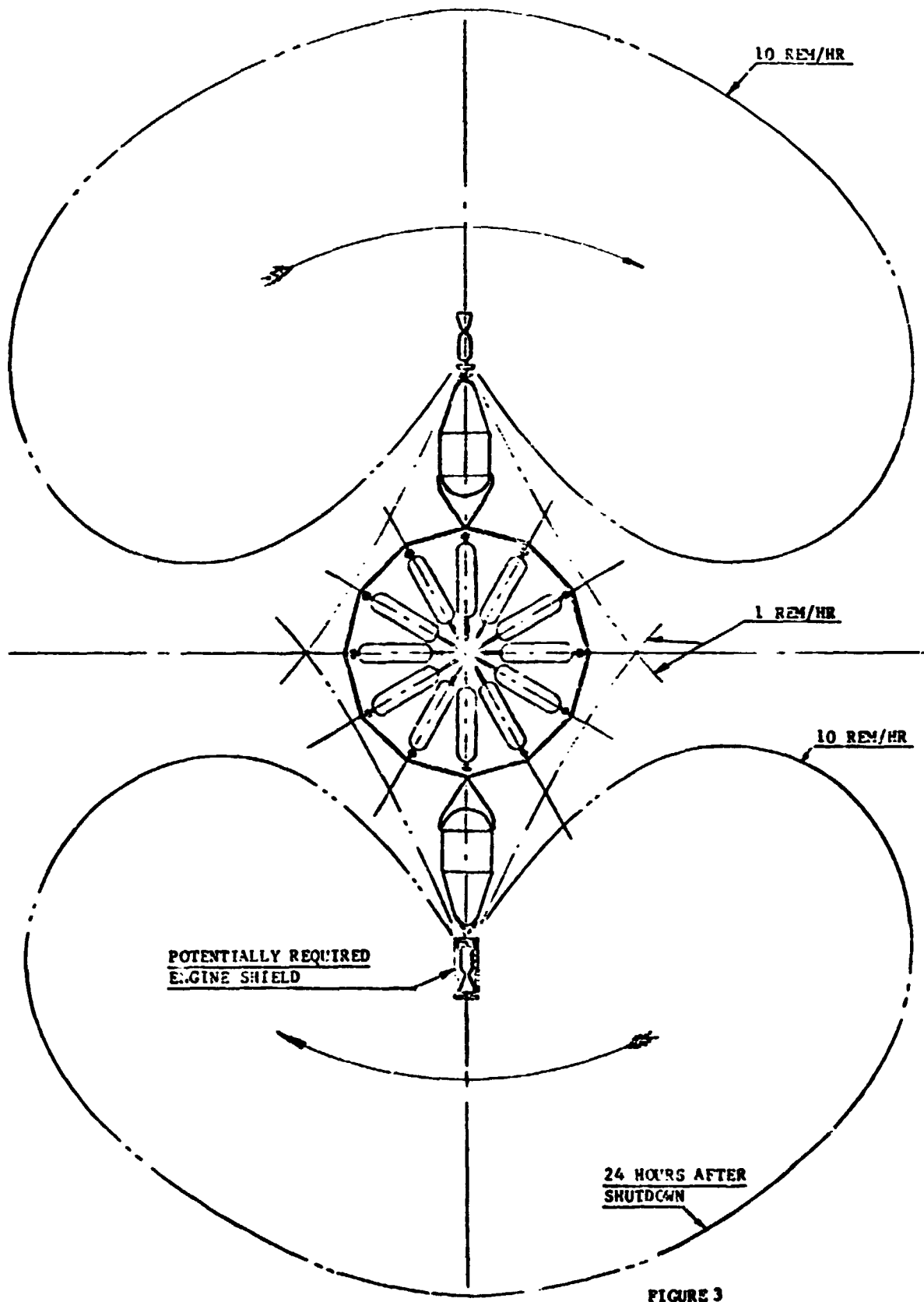


Figure 3 - Space Propellant Servicing Concept

A valid requirement to provide shielding for the engine in space would affect current design to the degree that component and piping arrangements might facilitate or inhibit the capability of remotely installing such a shield in a radioactive space environment. This possible requirement would tend to necessitate (1) a regular outer surface where a shield seal could be effected to isolate the reactor from the upper engine and vehicle and (2) an engine of reasonably compact diameter.

(b) Pre- and Postoperational Checkout

It is assumed that, before leaving the earth-orbital space station on a mission, the nuclear ferry will be subjected to a preoperational checkout. The objective of the checkout would be final verification that the vehicle and its subsystems were in complete readiness for the mission. The checkout would also be used to verify satisfactory accomplishment of any maintenance actions taken since the last mission. If needed, a post-operational checkout would be made after a mission. This checkout would be similar to the preoperational checkout except its purpose would be to determine requirements for maintenance that were not defined during the operational phase of the mission.

The primary effect on engine design would be the care required in selecting and providing diagnostic instrumentation. These requirements can probably be satisfied later during the engine development program.

(c) Repair or Replacement of Items by a Man in a Space Suit

A possible maintenance action for a man in a space suit is defined by assuming that a random-type failure has occurred on one of two small, redundant engine components during a mission and that the nuclear

ferry vehicle has completed the mission and returned to the earth-orbital base. Maintenance would be required prior to the next mission. (A vehicle tankage maintenance requirement might be satisfied by this same approach). Because of the low probability of this type of failure occurring, cost considerations dictated that maintenance capability not be provided for remotely removing the component module from the engine on the ferry. However, with portable shields used to reduce radiation to tolerable levels in the vicinity of the defective part, a team of technicians in space suits could effect the replacement. In doing so, they would reduce the down time of the vehicle that would have been required for engine replacement and would make possible full use of the engine life.

In studies to date, provisions for protection against radiation hazards by shielding have been primarily limited to protecting passengers and crew members during the operational phase of manned missions. Preliminary studies (Reference 11, attached as Appendix A) have shown the feasibility of portable shielding around the engine. Shielding studies in greater depth are required to determine the types of portable shields that will be required to protect men at the propellant depot, in the vehicle crew quarters, and possibly in the orbital space station when more than one vehicle is in the same vicinity. Similar studies are also needed to determine if these shields or similar shields could provide sufficient protection for direct manual maintenance of the engine or vehicle forward of the disk-shield location. Man's versatility in performing direct maintenance could greatly enhance the capability for future maintenance actions in space. Again, engine design would be affected to the degree that component and piping arrangements might facilitate or inhibit the capability of remotely installing such a shield in space.

(d) Maintenance Actions Involving Engine Replacement

Maintenance actions involved with engine replacement are

defined by assuming that a nuclear ferry vehicle has returned to the earth-orbital space station with a faulty engine component and requires maintenance prior to the next mission. The returning vehicle is located a sufficient distance from the space station to ensure radiation protection until cooldown flow to the reactor is shut off. Space tugs then bring out a portable shield and position it around the reactor, and the engine is removed from the vehicle, and the space tug takes it away for disposition. Space tugs bring up and position the replacement engine, which is also encapsulated in a portable shield if radioactive; and the engine is installed on the vehicle. The installation is checked out to determine that it is satisfactory to go ahead with refurbishment of the vehicle for the next mission. Final checkout of the installation is conducted as required during the preoperational checkout.

There is again a possible requirement for shielding an engine that has been operated, to protect personnel while disposition actions are being taken.

The capability to replace the engine on the vehicle in space appears to be the most important maintenance capability to be provided because the resulting extension of nuclear-ferry life affords significant opportunities for reducing program costs. If the concept is chosen wherein propellant tanks delivered to orbit by the EOS are then combined into a module of tanks that become part of the nuclear ferry, a change equivalent to engine replacement would be required after each mission. Also, it might be more cost effective to make the shielding changes required between manned and unmanned missions by replacing one type of engine with the other rather than attempting to modify the shield configuration while the engine is on the vehicle.

The capability to replace the engine must be accounted for in designing the engine-vehicle interface and must be provided for in the

space support equipment and facilities. Major cost expenditures would be justified to achieve fast, engine replacement. Detailed design of the engine-vehicle interface need not be shown on the current reference engine, but the requirements must be recognized and, early in the program, total coordination of this design with the space equipment and facilities must be effected. The engine should probably be replaced on the vehicle remotely. Engineering evaluation is required to determine what capability should be provided by the vehicle and what should be provided by external space support equipment.

(e) Disposition of an Engine Removed from Space Service

An engine that has been removed from the nuclear ferry will probably be either discarded or repaired, or may be held in a parking orbit away from the space station to await disposition for discard or repair. Some alternatives for disposition of such an engine are shown in Figure 4.

Engines will normally be removed from space service after their nuclear life has been expended and will probably be discarded. But engines may be held in orbit until it is convenient to schedule their discard. These engines may possibly require shielding to protect personnel during handling operations, but there are no other apparent influences on current engine design.

The decision as to whether or not engines that still have valuable nuclear life should be repaired in space will depend on the cost effectiveness of providing in-space maintenance capability. As discussed earlier, the cost effectiveness can not be determined until the

DISPOSITION OF ENGINE REMOVED FROM SPACE SERVICE

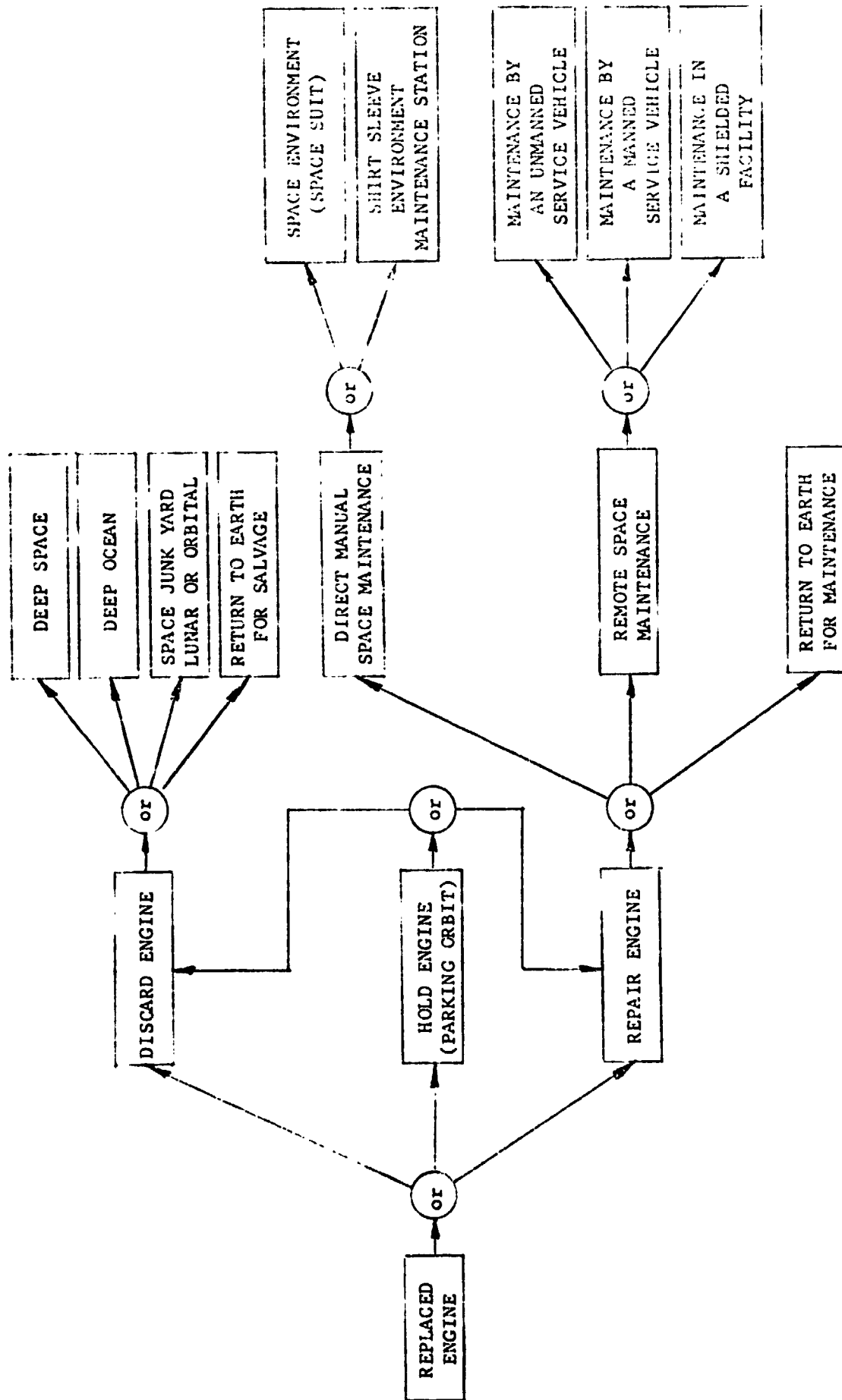


FIGURE 4

operational lives of all components are established and the costs of space maintenance equipment and facilities are better defined. The possibility that direct manual maintenance on a removed engine might be feasible with the use of portable shields must be further investigated. This feasibility might be enhanced by first allowing the removed engine to cool down while in a parking orbit. Man's versatility, even in a space suit, for performing random maintenance tasks without large additional costs appears very desirable. The possibility of performing space maintenance operations manually would be facilitated by the application to current design of the guidelines defined in the following section entitled "Maintenance during Ground Testing."

The use of space maintenance service vehicle or facilities to perform remote maintenance on the removed engine is feasible, although equipment and facilities that are versatile enough to repair random component failures appear to be elaborate and expensive. Further evaluation is warranted to assess such facilities from the standpoint of growth potential. A requirement to design the engine so flanges, connectors, and joints are provided that would permit space replacement of parts by using present-day manipulators and their remote tools would drastically constrain the design. Until the desirability of such a requirement is definitely established, the designer should provide only for easy access and basic simplicity of remote component removal to facilitate ground maintenance. If the desirability to replace a component or a number of components remotely in space is established in the future, the engine changes should be possible with minimum design perturbation.

2. Maintenance During Ground Testing

a. Maintenance experience in the Technology Program

Experience gained during reactor and engine testing

in the technology program is directly applicable to ground test maintenance of the NERVA engine. It is planned to conduct the NERVA reactor and engine ground tests at the Nuclear Rocket Development Stations in Nevada, where maintenance facilities, equipment and technical capabilities were proved during the technology program. The following activities are representative of the type of maintenance tasks performed in the technology program:

(1) The illusion of nozzle tube damage on a fired reactor, as noted by television viewing, binoculars and photographs was proved to be caused by lighting effects, through the use of a remotely applied surface coating.

(2) A bird was remotely removed after it fell into the upward firing reactor of NRX/EST (an engine systems test).

(3) Three turbine-power-control-valve actuators were manually replaced after partial power operation.

(4) The remote capabilities of the reactor maintenance, assembly and disassembly facility (R-MAD) were verified during the disassembly of experimental reactors after tests in the technology program.

(5) The technology engine XE-P was remotely installed on Test Stand ETS-1 and checked out. The engine was then remotely removed and returned for storage to the engine maintenance, assembly, and disassembly building (E-MAD) until completion of an underground test, after which the engine was again transported to the test stand, remotely reinstalled, checked out, and tested. After the test program, the hot engine was remotely removed from the test stand and returned to E-MAD for disassembly. Remote engine removal and reinstallation operations at the test stand interface (involving capabilities of making and breaking of fluid couplings, structural connections and in excess of 3000 electrical connections) were verified.

(6) The turbopump was manually removed and replaced on the test stand after partial power engine operation by utilizing test-stand shielding augmented by portable shielding.

(7) The turbine block valve was replaced after a partial power test.

(8) The capability for remote removal and reinstallation of the upper thrust structure module (UTSM) was developed in E-MAD.

(9) Final remote disassembly and inspection operations on XE-P in E-MAD have provided much experience that will be applicable to maintaining a hot NERVA engine after ground testing. Except for remote replacement of the UTSM, the engine was not designed for remote replacement of components; and the final disassembly could not have been reversed into reassembly. However, it was shown that the operation of the E-MAD facility, equipment, and personnel will permit remote ground maintenance of the NERVA engine.

b. Component Maintenance

The provision for future maintenance of a hot nuclear engine at the test site definitely influences current engine design. Maintainability design makes such maintenance possible or impossible. Although it is doubtful that maintenance in space beyond the replacement of the complete engine on the stage is justified, remote maintenance capability during ground testing will be a valuable program asset. The E-MAD facility with its assembly, disassembly and post-mortem bays, equipped with manipulators, overhead positioning systems, cranes, slings, and other remote maintenance equipment, was provided for the Technology Program and is available for maintenance during the NERVA development and qualification program. Since

facility and equipment expenditures will be relatively minor, hardware cost reductions due to maintenance will result primarily in program savings. In addition to reducing hardware costs, ground maintenance capability can provide time savings which also represents program savings. The capability to repair an engine by replacing components is particularly effective during the development phase when hardware quantities are limited.

After an engine has been operated at significant power, any maintenance internal to the pressure vessel and nozzle would be impractical. Consequently, remote component replacement capability at the site should be limited to the turbopumps, valves and actuators, the gimbal, and the control drum actuators external to the pressure vessel.

Factors that should be considered in current engine design to facilitate the replacement of components are as follows:

1. Arrange components, piping, electrical harnesses and structures to provide optimum accessibility.
2. Avoid loose parts during replacement activities by designing so parts are captive to the item being removed.
3. Provide for simplicity of motions and attachments in designing replacement capability. For example, use single axis motion to separate and install items.
4. Keep separation and replacement loads as low as practical.
5. Where possible, avoid a requirement for special equipment or tools and minimize through standardization the number of

different tools required to accomplish maintenance operations.

6. Minimize the disturbance of parts or components that are not being replaced.

7. Design for maintenance actions in space should consider the problem of excessive shock loads that could result from the initial impact of floating masses as replacement items are brought to the next assembly for installation. Provisions must be made to avoid contact at an angle or contact at significant velocity.

8. When practical, incorporate methods of ensuring precise alignment into the design of making parts. For replacing the engine in space a method such as cascaded guide pins will be required to effect gross, close, and precise alignment as the engine is brought to the vehicle for installation.

c. Modular vs Single-Component Packaging

Single component vs modularized component packaging was examined as a part of this study to determine the degree of modularization that should be included in the engine design. These were evaluated from the following standpoint:

Reliability (number of piping joints)

Logistics

Checkout

Diagnostic instrumentation

Maintenance problems

Reliability is enhanced by a reduction in the number of piping joints that is effected by modularization which results in a lower potential for system leakage.

Logistics does not enter into the evaluation since for either case, modular or single mount, the total spares would be the same.

Checkout for either case is probably the same although the installation during a maintenance action of a pre-checked-out module may require less engine checkout than that needed following a single component installation. This possible advantage would stem from elimination of any interaction effects.

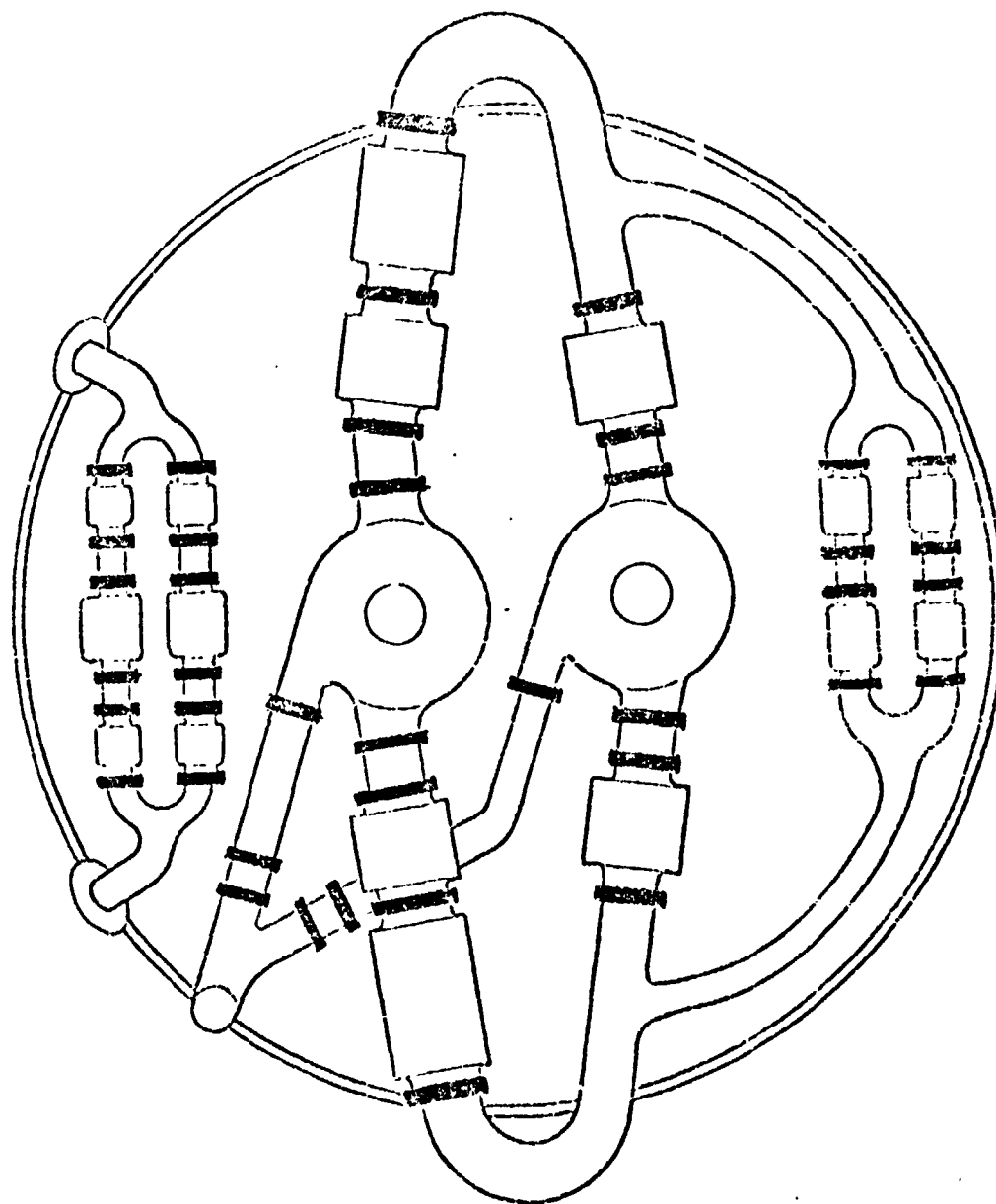
Diagnostic-instrumentation considerations should favor modularization because fewer instruments should be required to pinpoint trouble within a module compared with pinpointing trouble to each component.

Maintenance problems are the most important consideration of these parameters. It is extremely important during maintenance work to be able to remove a component without needing to move or remove other equipment. This aspect of interlocking interfaces is illustrated in Figures 5 and 6.

These figures are overly simplified and are strictly artist's concepts to illustrate the point. However, Figure 5 illustrates the difficulty of maintaining a single axis component removal with individual components and a comparison with Figure 6 illustrates how modularization will eliminate piping joints.

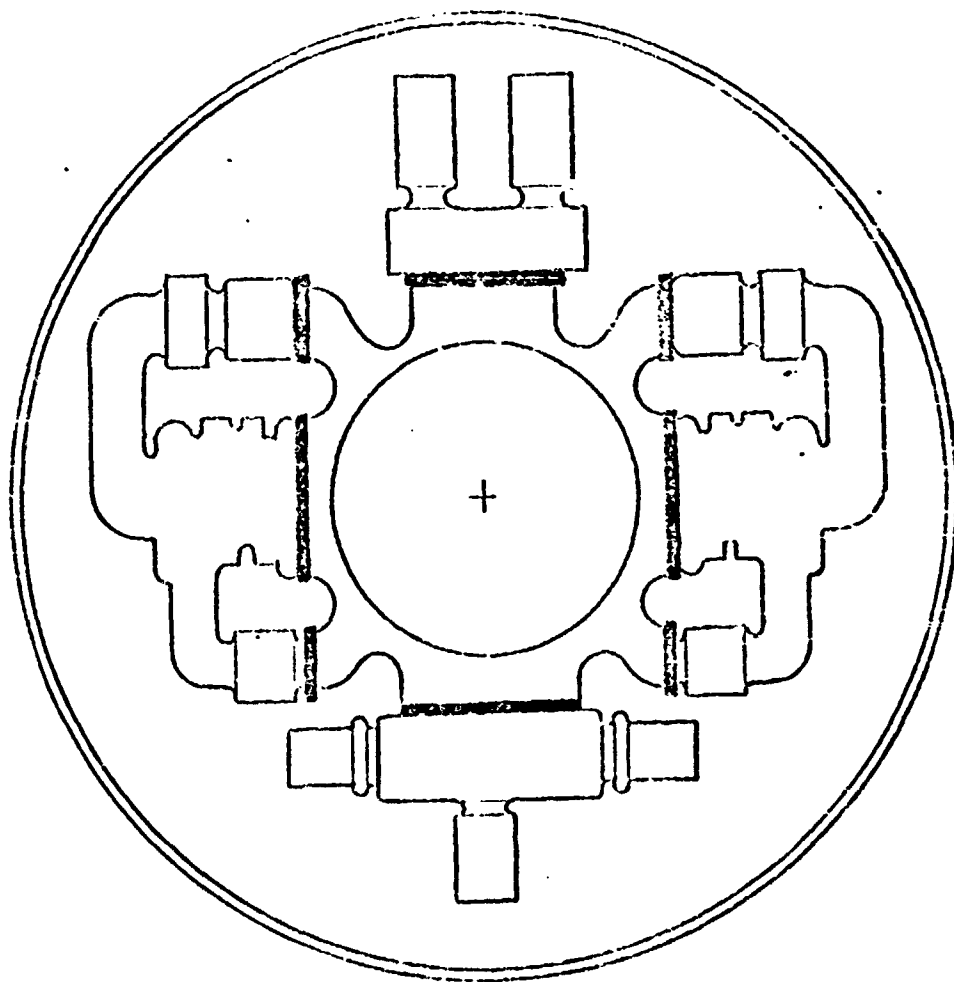
As a result of this study and engine packaging studies, the components are grouped for modularization as follows:

The structural support cooldown module consists of the following components:



INDIVIDUAL COMPONENTS

FIGURE 5



MODULARIZED COMPONENTS

Figure 6

SS3V1

SSBV2

SSCV1

SSCV2

Any interconnecting plumbing as required.

NOTE: The SSCV's perform as part of the NSS (Specification No. CP 677555) but are physically part of this module.

The turbine bypass control valve module consists of the following components:

BBV1

BBV2

BCV1

BCV2

Any connecting plumbing as required.

Two TPA modules consist of the following components:

TPA Module #1

TPA1

TDCV1

TBV1

PDKV1

Any connecting plumbing
as required

TPA Module #2

TPA2

TDCV2

TBV2

PDKV2

Any connecting plumbing
as required

The cooldown supply modules consists of the following components:

CSOV1

CSOV2

CSCV1

CSCV2

Any connecting plumbing as required.

Single components not included in a module.

PSOV1

PSOV2

3. Maintenance on the Launch Pad

Nuclear-engine maintenance on the launch pad will be very similar to that for any rocket engine on the launch pad. The engine will not have been operated at powers that would necessitate working in a significant radiation environment, and maintenance can be performed by normal work crews using standard tools.

It is anticipated that the nuclear ferry vehicle will have been assembled and checked out prior to installation on the Saturn V system. It is also reasonable to assume that this installation will have been checked out prior to launch-pad delivery of the Saturn V system that will transport the nuclear ferry vehicle to earth orbit. Because the nuclear engine will not be fired until after servicing in earth orbit, it is doubtful that launch-pad checkout of the nuclear engine would be extensive enough to reveal faulty operations that went undetected in the earlier inspections. However, to save valuable time during these earlier inspections and to provide for contingencies on the launch pad, the maintainability guidelines listed in Paragraph IV.B.2.b. should be incorporated in current design to reduce the down time resulting from maintenance actions identified by any of these checkouts.

C. SAFETY

The capability for satisfying NERVA engine safety requirements is unaffected by the cost trade-offs evaluated in this report and safety was not a parameter in the types of decisions that evolved from this Trade Study.

Safety will be a most important parameter in the eventual selection of space maintenance concepts that have been discussed in this report.

Safety requirements applicable to space maintenance operations and to the design and qualification of space maintenance facilities and equipments will be as stringent as those applied to the operational hardware and to mission operations. Dose rates that personnel may encounter during maintenance activities are discussed in Appendix A.

APPENDIX A
AEROJET NUCLEAR SYSTEMS COMPANY
SACRAMENTO, CALIFORNIA

25 March 1970
7831:6246N:JCC;vg

TO: W. E. Stephens/A. D. Cornell

FROM: J. C. Courtney

SUBJECT: Estimate of Post-shutdown NERVA Radiation Environment

COPIES TO: D. Buden, R. M. Beattie, C. E. Dixon, W. Durkee, R. V. Evleth,
E. J. Gilchrist, C. K. Leeper, B. Mandell, I. L. Odgers,
W. E. Stephens, W. A. Sutter, R. K. Swain, W. O. Wetmore

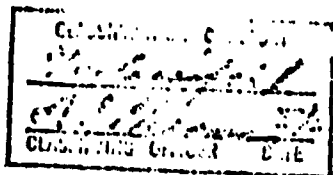
ENCLOSURE:

- (1) Unshielded Shutdown Dose Rate Map
- (2) Unshielded Engine Configuration
- (3) Shutdown Dose Rate Map with Engine Disk Shield
- (4) Isometric of Side Shield Concept
- (5) Effect of Side Shield on Dose Rate
- (6) Side Shield for Vertical TPA, External TS Engine Configuration
- (7) Side Shield for Canted TPA, Internal TS Engine Configuration
- (8) Side Shield for Horizontal TPA, Internal TS Engine Configuration
- (9) Post Shutdown Whole Body Gamma Dose Rates
- (10) Gamma Dose Rates from Engine Activation Only
- (11) Locations of Detectors

Estimates of the post-shutdown NERVA radiation environment were made to support the maintainability trade study. After shutdown sources consist of gammas from fission products in the reactor core and activated engine components. It should be pointed out that the activation calculations are quite sensitive to the types and weights of materials used as well as the spectrum and intensity of incident neutrons. Accordingly, the activation calculations should be considered as gross estimates for a given set of assumptions.

Enclosure (1) presents the gamma dose rates 24 hours after shutdown for a NERVA without the disk shield. These results are for the configuration shown in Enclosure (2) based on AGC Dwg 1136390. The results would be the same (within the accuracy of the calculations) for other engine configurations without a disk shield. Enclosure (3) illustrates the effect of an engine disk shield on the dose rate contours forward of the core center. Note that this shield protects only a very limited volume. Because of the closeness of the contours, a small movement out of the shadow of this shield could cause a marked increase in the gamma dose rate.

Less restricted access to the engine could be attained with an additional side or clamshell shield that could be moved in place after shutdown. Enclosure (4) presents an isometric view of this concept. The effect of this type of



APPENDIX A

W. E. Stephens/A. D. Cornell


- 2 -

25 March 1970


shield on the dose rate map is seen in Enclosure (5). Side shield configurations that accommodate various engine layouts are shown in Enclosures (6), (7) and (8). The weights of these clamshell shields is given in Enclosure (9).

Enclosure (9) presents a more complete picture of the effect of these shields on the post shutdown environment. Neutron activation of engine components above the PVARA (forward of the pressure vessel dome) can result in important sources. The clamshell shields around the pressure vessel and nozzle would have no effect on this source. If the lower part of the engine is shielded, then the predominant radiation source can be the components above the PVARA. The estimates of whole body dose given in Enclosure (9) take into account that the human body is made up of many point detectors distributed over a volume. So all parts of the body are not in the same dose rate field.

An attempt to map the activation dose rate field is presented in the next two enclosures. Enclosure (10) presents dose rates at the various points shown in Enclosure (11) for several times after shutdown from a 10 minute run at full power. These dose rates are from activation gammas from those engine components forward of the pressure vessel dome. That is, there is no contribution from either activation gammas from engine below the pressure vessel dome or the fission product gammas in the core. These dose rates are appropriate for point detectors rather than for human bodies. Detectors 4 and 5, labeled whole body, are estimates of dose rate at points appropriate to the location of the torso of a man if he was working on the turbopump assembly.


J. C. Courtney
Nuclear Analysis Group
Engine Systems Dept.

Approved:


E. A. Warman, Supervisor
Nuclear Analysis Group
Engine Systems Dept.

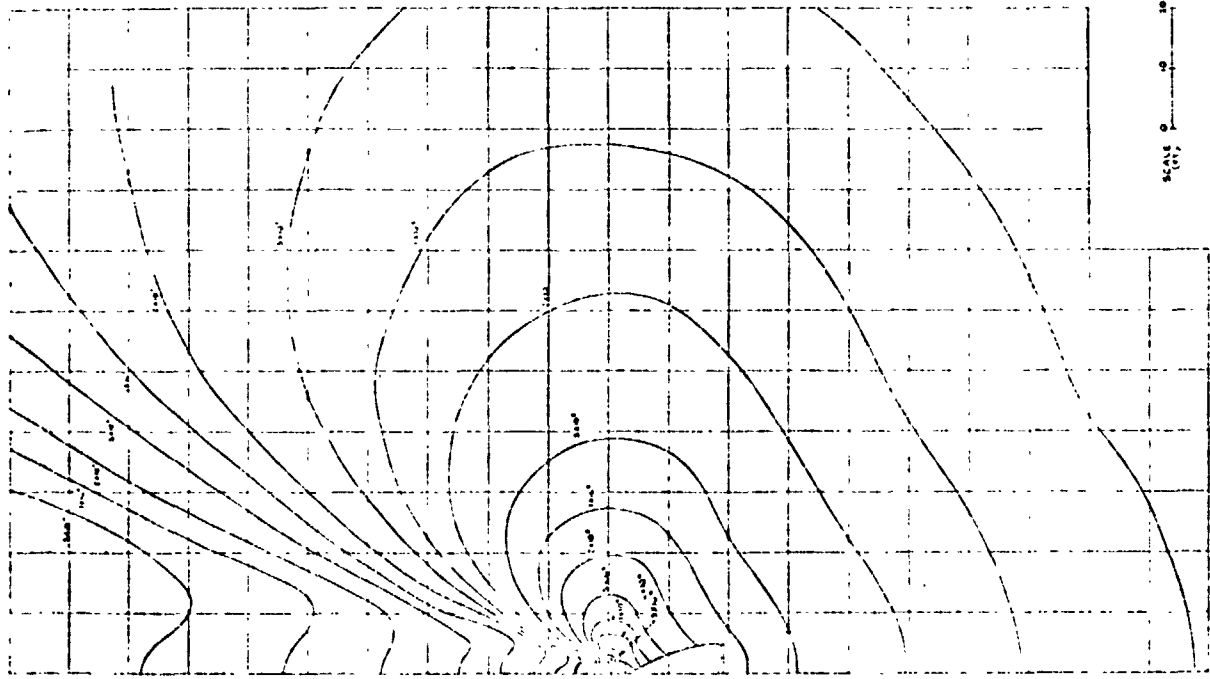
APPENDIX A



76 112.1114
2900 (1)

SHUTDOWN DOSE RATE MAP

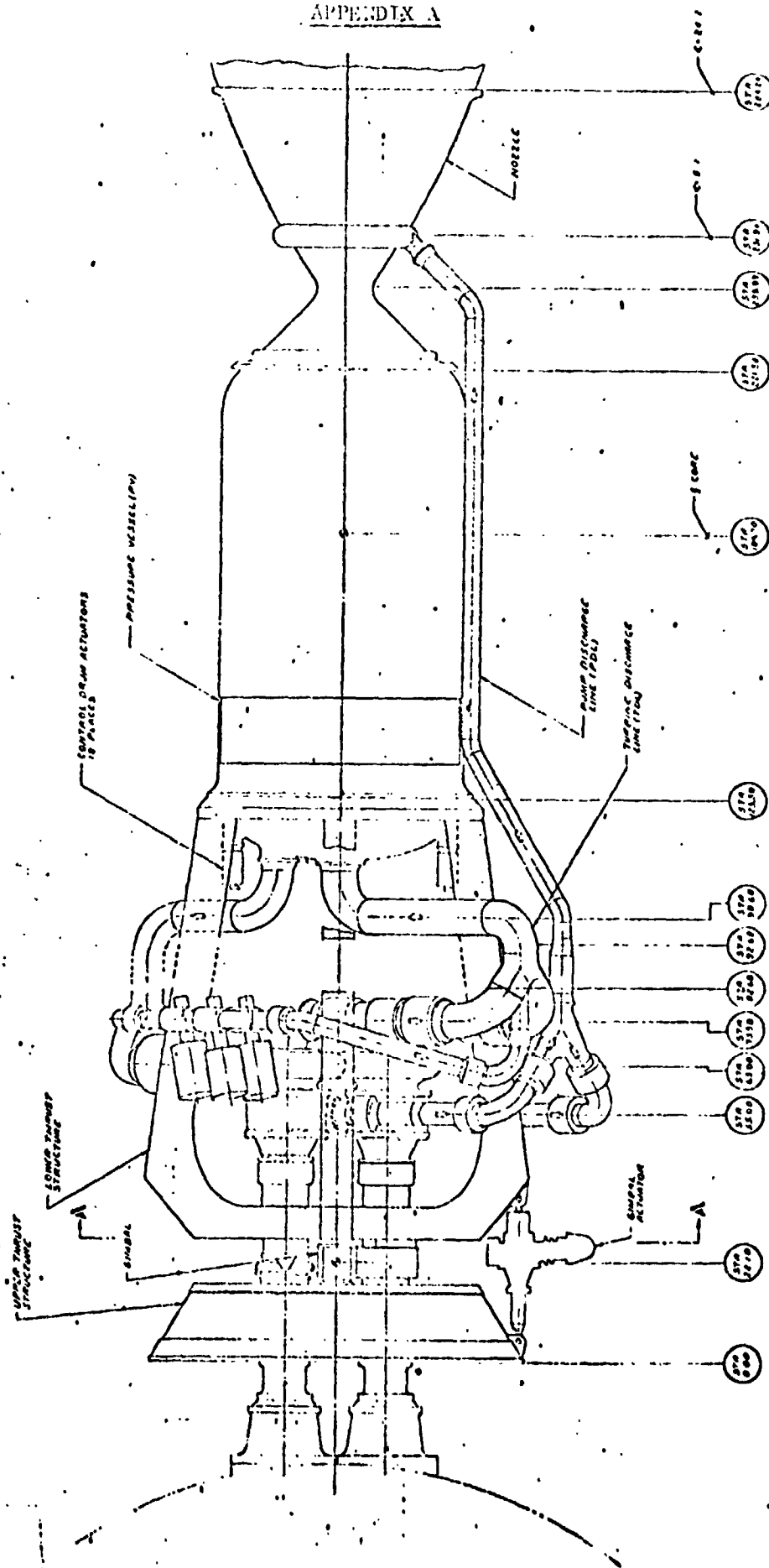
NUCLEAR POWER PLANT NO. 1, TUNICA, MISSISSIPPI
COMPARISON OF EAST OF A RIVER



SCALE 0 10
feet

- 1000 R/hr
- 500 R/hr
- 250 R/hr
- 125 R/hr
- 62.5 R/hr
- 31.2 R/hr
- 15.6 R/hr
- 7.8 R/hr
- 3.9 R/hr
- 1.95 R/hr
- 0.975 R/hr

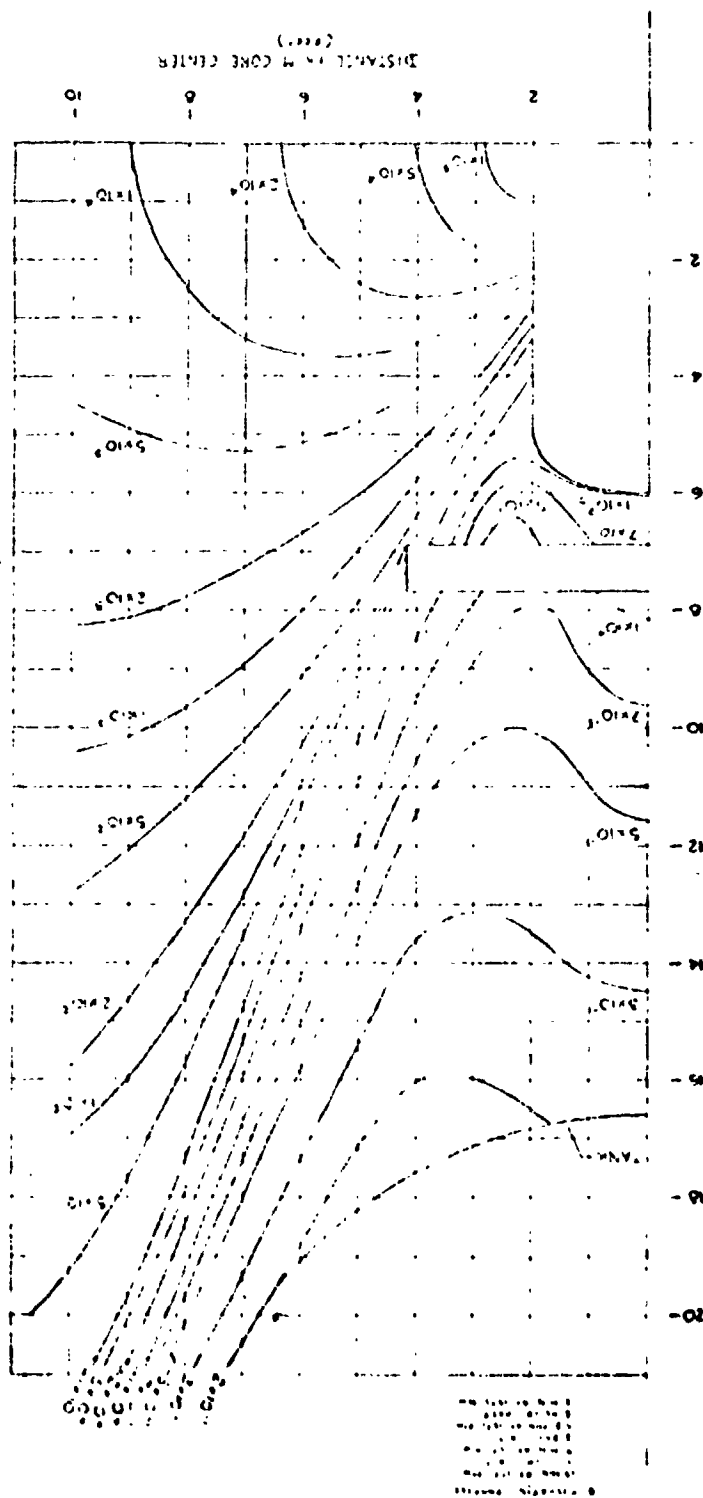
(c) admission



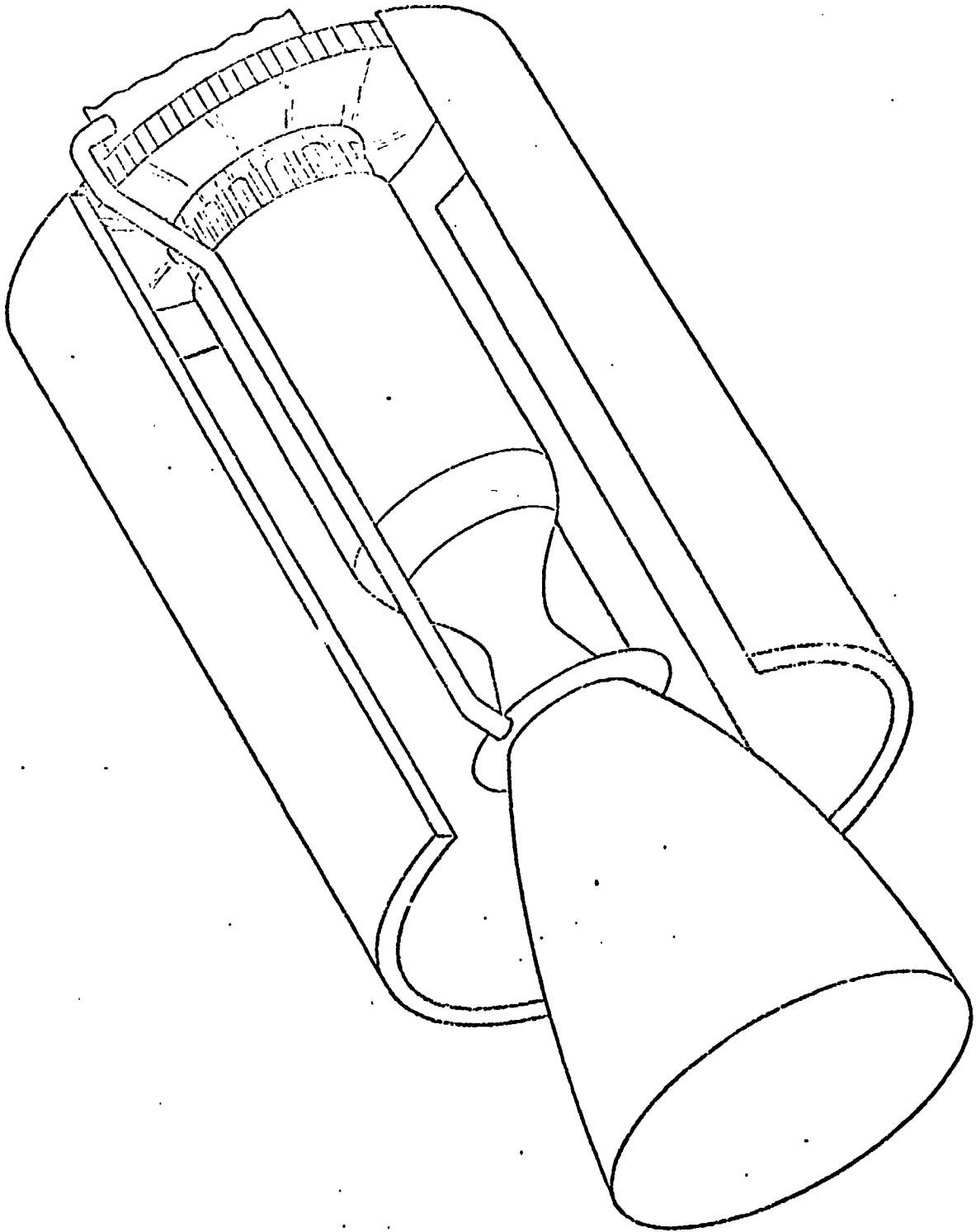
APPENDIX A

SHUTDOWN DOSE RATE MAP HERA ENGINE WITH EXTERNAL SHIELD 24 HOURS AFTER LAST OF 4 BURNS*

UNITS: mRDS/HK
 FEB 1978

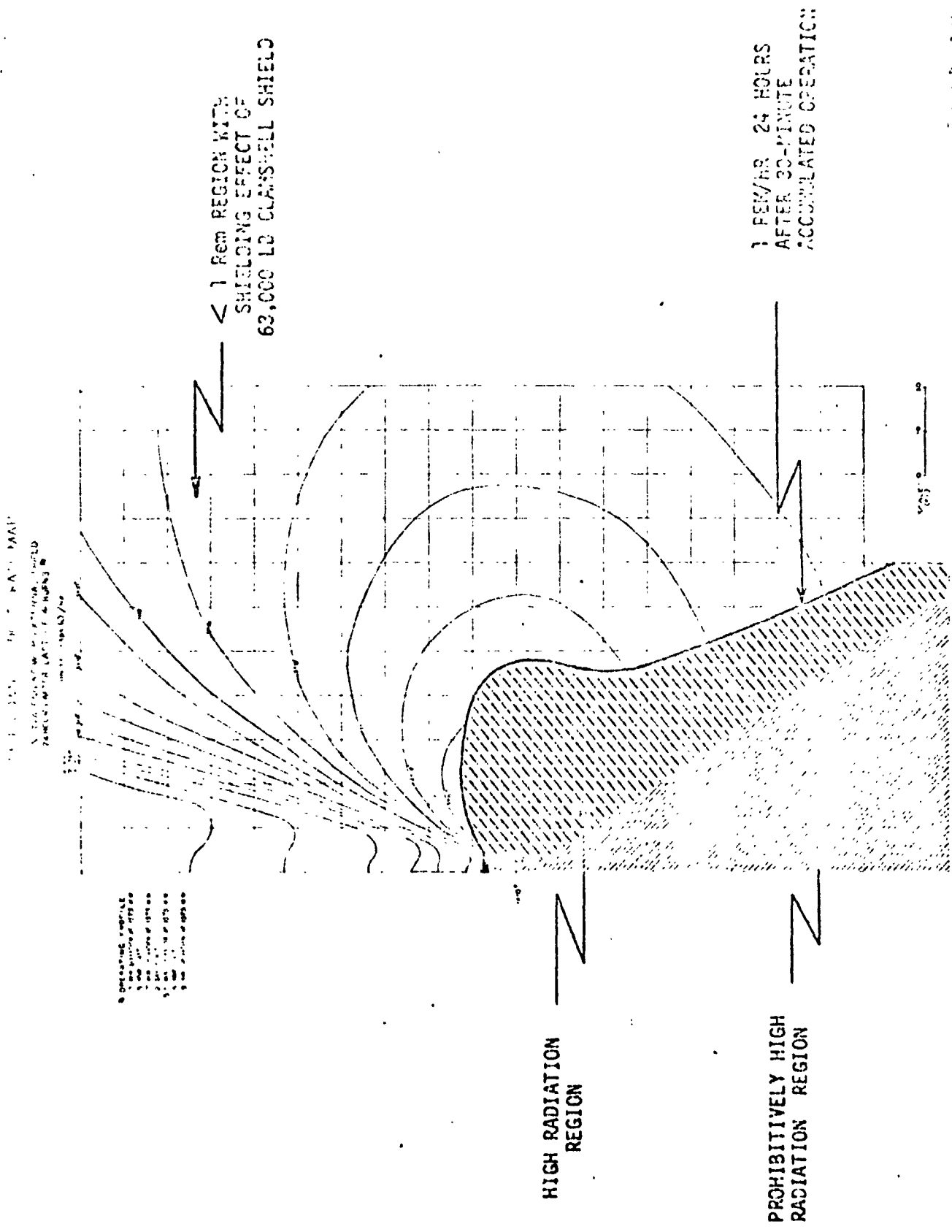


ENGINE RADIATION SHIELD

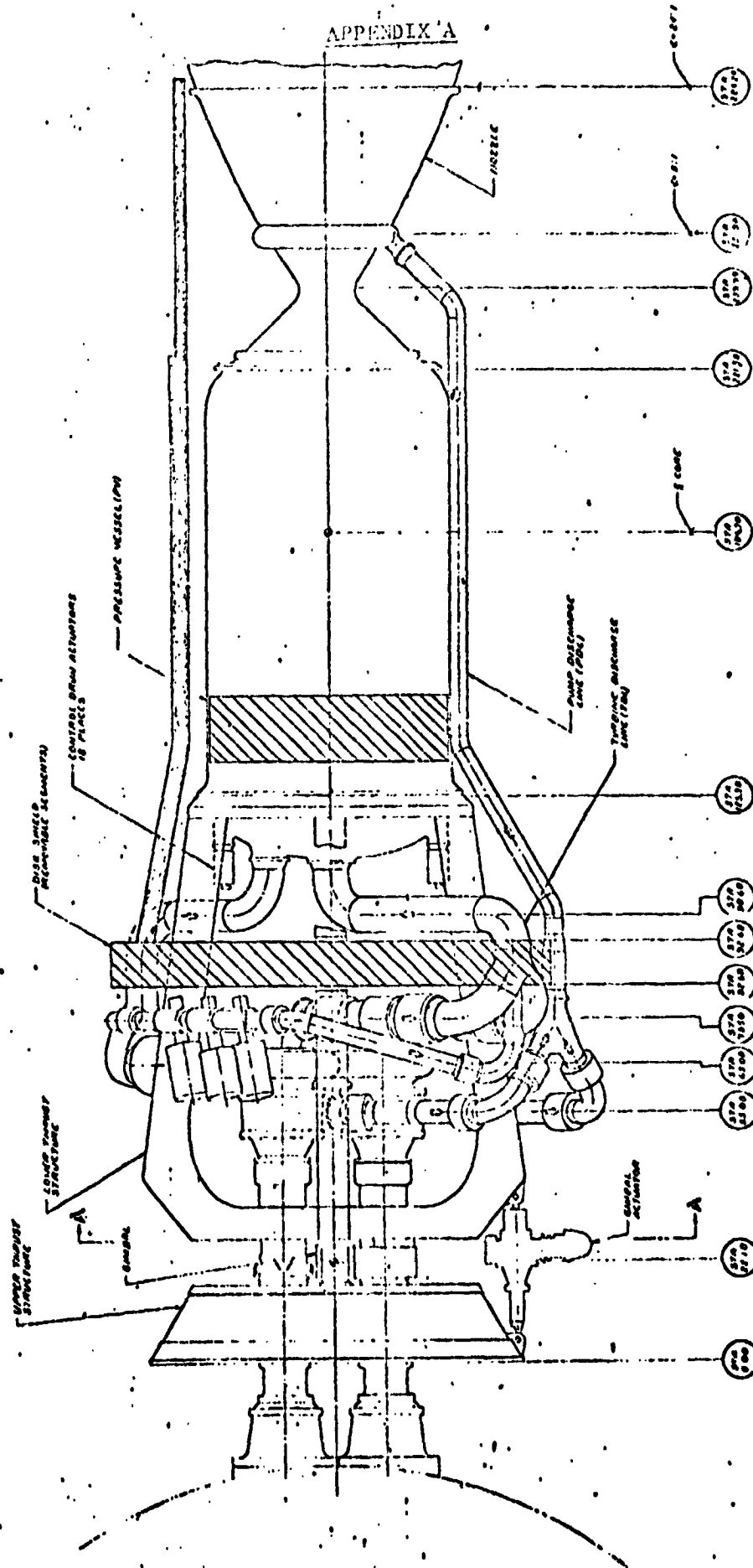


APPENDIX A

100 LBS
100 (100)



APPENDIX 'A'



(c) attorney's fee



[illegible]

POST SHUTDOWN WHOLE BODY GAMMA DOSE RATES

Configuration	Dose Rate (Rem/hr) @ Time After Shutdown			
	24 Hours		7 Days	
	Nozzle & + Upper**	Engine = Total	Nozzle & + Upper**	Engine = Total

Shielding During Operation

3,300 lbs Int.

None

$$100 + 30 = 130$$

$$21 + 13 = 34$$

$$5 + 11 = 17$$

3,300 lbs Int.

Inverted L Clam-shell (~61,000 lbs) plus 3000 lb Partial Disk

$$1 + 30 = 31$$

$$0.3 + 13 = 13.3$$

$$0.1 + 11 = 11.1$$

3,300 Partial Disk

3,300 lbs Int.

Cylindrical Clam-shell (~66,000 lbs) plus 4000 lb Partial Disk

$$1 + 24 = 25$$

$$0.3 + 10.5 = 10.8$$

$$0.1 + 8.7 = 8.8$$

4,000 Partial Disk

3,300 lbs Int.

Cylindrical Clam-shell (~63,000 lbs) plus 10,000 lb Full Disk

$$1 + 1.5 = 2.5$$

$$0.3 + 0.7 = 1.0$$

$$0.1 + 0.6 = 0.7$$

10,000 Full Disk

APPENDIX A

Assumptions/Comments

- 1) Lead Clamshell shields in place.
- 2) Synchronous Orbit Ferry Mission Run Profile (i.e., 30 minutes @ full power).
- 3) For 300,000 lbs LH₂ consumption within 30 days (i.e., 60 minutes at full power), double dose rates at 7 and 30 days.

*Includes activation of engine components below Pressure Vessel dome.
 **Activation of engine components below Pressure Vessel dome.

DOSE RATE IN R/HR AS A FUNCTION OF LOCATION AND TIME AFTER SHUTDOWN

Detector	Location	Time After Shutdown				
		0	1 Hr.	10 Hr.	1 Day	7 Days
1	Contact	20,000	133	20.5	7.3	4.2
2	Contact	10,000	360	56.8	9.8	4.2
3	Contact	3,100	149	19.0	2.2	0.9
4	Whole Body	1,580	42	7.2	1.2	0.5
5	Whole Body	2,480	45	8.6	1.7	0.8
6	Approach	404	7.4	1.3	0.4	0.1
7	Approach	490	7.0	1.2	0.3	0.1

Assumptions/Conditions

- 1) No engine disk shield.
- 2) Only activation sources in engine considered (i.e., fission products are neglected).
- 3) Activations take place over 10 minutes at full power.
- 4) Materials not selected to minimize activation.
- 5) Unperturbed neutron fluxes used in activation calculation.
- 6) Activation due to epi-thermal neutron flux alone; the thermal activation not included because of uncertainties in PVARA thermal flux leakage.

APPENDIX A



NRD

POST SHUTDOWN RADIATION LEVELS



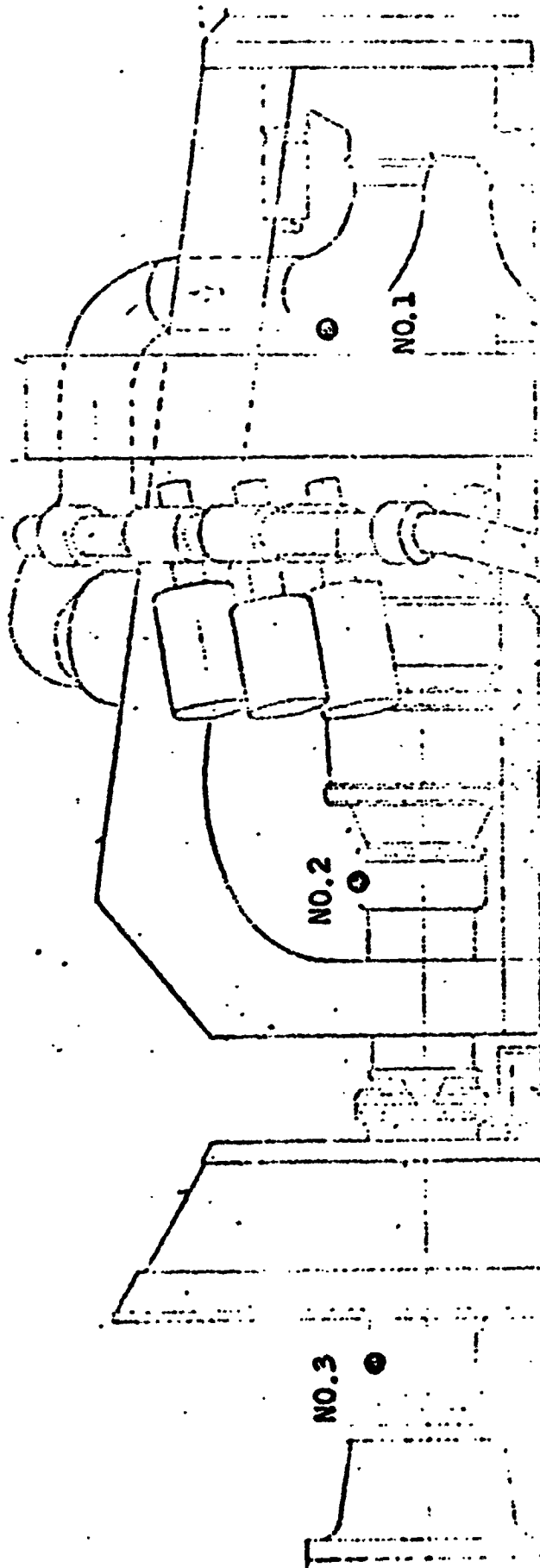
↑
□ NO.7

↑
□ NO.6

○ NO.5

○ NO.4

APPENDIX A



● CONTACT POINTS ○ WHOLE BODY DOSE POINTS □ APPROACH DOSE POINTS (12-1/2 FT FROM QL)